THE IMPACT OF HIGH PERFORMANCE TECHNOLOGY ON THE DESIGN OF NAVAL SHIP STRUCTURES

William David Whiddon

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by

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ABSTRACT

Hydrofoils display superior structural efficiency when compared with conventional displacement monohulls. Eight hydrofoils and eleven monohulls were analyzed based on a comparison of selected structural weight fractions and specific weight rations to identify and explain the various trends. A parametric model was employed to determine that the utilization of aluminum in monohulls could reduce the structural weight by an average of 39 percent which is 73 percent of the structural efficiency advantage enjoyed by hydrofoils. The remaining difference was the result of such factors as design loads, safety factors, level of design detail, and construction techniques. It was determined that hydrofoils are designed to higher load profiles than monohulls. This is the reverse of the expected trend. Therefore, the differences in the factor of safety, design detail, and construction techniques combine to overcome the higher hydrofoil load profile and account for the residual differences in the structural efficiency advantage of hydrofoils.

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NOMENCLATURE

W_n	Weight of a functional category, where n is a subscript defining the category

Definition of subscripts (n)

B	Ballast
DH	Deckhouse structure
FD	Foundations
FDL	Foundations minus foil supports
FF	Free flooding liquids
H	Hull structures
HP	Hull plating
HS	Hull supporting structures
LS	Light ship
ME	Machinery and equipment
MEL	Machinery and equipment minus foils
MR	Margins
MS	Miscellaneous structures
S	Ship structures
W	Welding

Numerical subscripts refer to the Ship Work Breakdown Structure (SWBS)[3]

e.g., W_{116} = Weight of longitudinal framing

a	Longside dimension of panel, inches
B	Beam of ship at design waterline, feet
BM	Primary longitudinal or side bending moment, foot-tons
BM_A	Actual measured values of primary longitudinal bending moment, foot-tons
BM_D	Design values of primary longitudinal bending moment, foot-tons
b	Shortside dimension of panel, inches
C	Weight coefficient of conversion of an equivalent structure from steel to aluminum
C_L	Support constraint coefficient for monohull design load distribution
C_t	Material constant for monohull minus plating thickness
D	Depth of hull at midship, feet
Δ	Full load displacement of ship, tons
DMF	Dynamic magnification factor for hull impact pressures
DWL	Design waterline
E	Material modulus of elasticity, pounds/(inch)^2
H	Hydrostatic head, feet
H_W	Trochodial wave height, feet
I_{yy}	Moment of inertia of a structural element about the y axis, (inches)^4
I_{zz}	Moment of inertia of a structural element about the z axis, (inches)^4
K	Column allowable stress slenderness reduction constant

K_t	Geometrical constant for monohull minimum plating thickness
K_4	End condition coefficient for slenderness ratios of columns
L	Length of ship between perpendiculars, feet
ℓ	Transverse frame spacing, inches
M	Bending moment due to local loading, inch pounds
NA	Neutral axis of a structural element
P	Static equivalent of hydrostatic or hydrodynamic pressures, pounds/(inch)^2
PSF	Pounds per square foot
PSI	Pounds per square inch
R	Radius of gyration of structural element cross section, inches
r^2	Coefficient of determination for linear regression curve fitting techniques
S	Longitudinal frame spacing, inches
σ_{AC}	Maximum compressive stress due to either primary longitudinal bending or local axial forces, pounds/(inch)^2
σ_{ALL}	Allowable design stress, pounds/(inch)^2
σ_{AT}	Maximum tensile stress due to either primary longitudinal bending or local axial forces, pounds/(inch)^2
σ_B	Allowable plate buckling stress, pounds/(inch)^2
σ_C	Allowable column stress, pounds/(inch)^2
σ_{SC}	Maximum compressive stress due to local secondary loading, pounds/(inch)^2
σ_{ST}	Maximum tensile stress due to local secondary loading, pounds/(inch)^2
σ_{SU}	Allowable ultimate strength of supporting structure, pounds/(inch)^2

σ_u	The stress resulting from the maximum load the structural element can take without gross failure, pounds/(inch)^2
σ_{up}	Allowable ultimate strength of plating, pounds/(inch)^2
σ_{um}	The ultimate strength of a material, pounds/(inch)^2
σ_y	The stress resulting from the maximum deformation that can be allowed without detriment to safe operation, pounds/(inch)^2
σ_{ym}	The yield strength of a material in tension, pounds/(inch)^2
σ_{ymc}	The yield strength of a material in compression, pounds/(inch)^2
σ_1	Stress due to primary longitudinal bending moment, pounds/(inch)^2
σ_{1A}	Allowable stress resulting from primary longitudinal bending moment, pounds/(inch)^2
σ_2	Stress due to secondary of local loading, pounds/(inch)^2
t	Plate thickness, inches
∇	Total volume of ship, (feet)^3
V_{DH}	Volume of deckhouse, (feet)^3
V_H	Volume of hull, (feet)^3
VCG	Vertical center of gravity, feet
W_A	Weight of ballistic protection, tons
W_I	Weight of fire insulation, tons
W_{SA}	Weight of equivalent aluminum structural system of existing steel structures, tons
W_{SAL}	Weight of equivalent aluminum structural system, tons
W_{SD}	Weight reduction resulting from change from steel to aluminum in existing steel structures, tons

W_{SDA}	Total weight reduction resulting from change from steel to aluminum hull material, tons
w	Distributed design load resulting from secondary or local loading, pounds
Y	The distance of the structural element from the neutral axis in y direction, feet
Z	The distance of the structural element from the neutral axis in z direction, feet

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CHAPTER 1

INTRODUCTION

Generally, high performance ships such as hydrofoils, surface effect ships, and air cushion vehicles display better performance in both speed and seakeeping than their conventional displacement monohull counterparts. The desirable advantages of the high performance vehicles are achieved through the incorporation of both a specialized sustension system which decouples the hull-sea interaction and low weight and volume impact subsystems which allows more installed horsepower thereby increasing the maximum speed. Among the high performance ships that appear viable for general military application, the hydrofoil displays the most desirable performance in the displacement regime populated by the majority of the conventional displacement monohulls. Hydrofoils utilize a foil system to provide dynamic lift thus eliminating the hull-sea interface. Marinized second generation aircraft derivative gas turbines have been chosen as prime movers for hydrofoils due to their lower horsepower to weight characteristics.

Recently, several studies have been conducted to identify the design differences in hydrofoils and monohull displacement ships. Grostick, in reference 1, identified some of these design differences and postulated that if hydrofoil standards were applied wholesale to a monohull,

the space and weight saved could be diverted to either additional payload, or the improvement of any other design feature. However, the level of analysis was general in nature and only considered four ships. No attempt was made to determine the applicability of the hydrofoil design standards to a monohull.

In reference 2, Fahy went a step further and tried to ascertain the applicability of hydrofoil design standards to monohulls. This analysis was based on a comparison of detailed weight fractions and specific weight ratios of two hydrofoils and two monohulls. It was determined in this study that a considerable weight reduction could be realized through the application of hydrofoil design standards to the structural system. This would make more weight available for payload. The study concluded by stressing that high performance standards cannot be applied in a wholesale manner. Careful analysis is required to determine the applicability of these design standards.

Both studies limited the analysis to a hydrofoil and a patrol boat or a destroyer in two displacement regimes. The patrol boat and destroyer were appropriate choices since the future generations of the high performance craft will probably supplant these ship types because of their superior operational performance.

The purpose of this study is to ascertain those factors contributing to the higher structural efficiency of hydrofoils as compared to monohulls.

There are five basic reasons that present themselves as possible candidates for the differences in the structural weight of the opposing vehicle concepts. These include differences in:

1) Materials
2) Loads
3) Safety Factors
4) Detail of Design
5) Construction Techniques

To quantify the impact of material differences and highlight those other factors which contribute to the structural efficiency superiority of hydrofoils, eight hydrofoils and eleven monohulls are compared in Chapter 2. Structural weight fractions and specific weight ratios are compared and trends identified. Special attention is paid to the explanation of these trends and their correlation to the various factors which cause the lower structural weight in hydrofoils.

The design load envelopes and some actual measured service loads are compared in Chapter 3. Both the magnitude of design loads and their correlation to service conditions

are pursued to ascertain the relative ranking of the loading each vehicle is designed for.

The design criteria and methodology of both vehicle concepts are outlined in Chapter 4. The basic design approaches, failure analysis, and allowable stress criteria are identified. This leads to a first order determination of the opposing factors of safety or conservatism indices.

The final conclusions of the study were that the material differences accounted for the overwhelming majority of the structural efficiency enjoyed by hydrofoils. The remaining differences were the result of such factors as design loads, safety factors, level of detail of design, and construction techniques. It was found that the hydrofoils are designed to higher load profiles which is contrary to the expected trend. The differences in the factor of safety, design detail, and construction techniques combine to overcome the higher hydrofoil load profile and account for the residual differences in the structural efficiency advantage of hydrofoils over monohulls.

CHAPTER 2

STRUCTURAL WEIGHT TRENDS

To quantify the impact of high performance technology on the design of naval ship structures, a large number of hydrofoils and monohulls are analyzed based on a comparison of selected structural weight fractions and specific weight ratios. Trends are identified and explained. Special emphasis is placed on the decoupling of the material difference in order that the impact of the other factors affecting the structural weight can be quantified.

The ship selection criteria and the ships chosen are presented in Section 2.1. The definitions, development, and significance of the various indices employed in the study are discussed in Section 2.2. In Section 2.3 the indices are compared and trends identified and explained. The impact of aluminum as a hull material is identified for the design of five monohulls. An overall summary and conclusions of the analysis are provided in Section 2.5.

Section 2.1 - Selection of Ships

Hydrofoils were selected as the high performance ships because the configuration of their hull structural subsystem most nearly resembled that of the conventional displacement monohull. Also, the hydrofoils provided the most complete

accurate data base with which to work. Destroyers and patrol boats were chosen as the conventional displacement monohulls since they fall in the same displacement regime as hydrofoils.

The following general guidelines were used in the selection of the ships considered:

- --designed to military standards as a combatant
- --sufficient design data available
- --level of detail of ship design
- --adequacy of ship population to determine size trends
- --adequacy of ship population to determine material impact

2.1.1 Hydrofoils

The hydrofoils were chosen for a variety of reasons. The PGH-1, PGH-2, PCH-1, and AGEH-1 are test craft built to varify the validity of the hydrofoil concept as a military combat system. They were included since they were designed to military standards and due to an inadequacy in the hydrofoil data base. The PHM-1 was included because it met all the selection criteria. It was considered in the studies conducted by Grostick [1] and Fahy. [2] The HYD-7, HOC, and HYD-2 are preliminary designs for future generation long endurance fully militarized hydrofoils. These designs were included to provide data for the upper region of the size regime.

2.1.2 Monohulls

The monohulls selected were all combatants designed to military standards. Since the design of monohull structures has not changed appreciably over the last several decades, monohulls were not limited to recent designs. The PGG, PCG, and MONO-3 were included even though they are preliminary designs of two patrol craft and a destroyer respectively. The PGG and MONO-3, along with the PG-84 were considered to determine the impact of aluminum hull structure as well as provide ships with similiar prime movers as the hydrofoils. The PCG was included to provide a steel hull monohull in the lower size regime and because it has gas turbine propulsion. The DD-963 and FFG-7 were included because they represent the most recent combatant monohull design in construction as well as having gas turbine propulsion. The FF-1033, FF-1037, FF-1040, FF-1052, and DDG-2 were considered to provide an enlarged data base since they are representative of typical monohull combatants. Both the PG-84 and FFG-7 were considered by Grostick [1] and Fahy [2] in their analysis.

Section 2.2 - Definition of Indices

In order to ascertain the impact of hydrofoil technology on monohull structural design, several parameters were developed which normalize the various weight groups that make up the structural weight of a ship. The development

of these parameters required an organized functional classification system to define the weights and volumes which were used in the determination of the indices. The selection of the indices to be studied was based on their ability to indicate the effect of those factors which result in the structural differences in hydrofoils and monohulls.

2.2.1 Functional Classification

There are several formalized classification schemes for breaking down the weights of combatant ships into the functional areas, among them the Bureau of Ships Consolidated Index (BSCI) and the Ship Work Breakdown Structure (SWBS).[3] This study will follow the SWBS system basically in dividing the various weight groups. The definitions of the weight groups considered are included in Appendix A. For those ships which were broken down into the BSCI weight groups, the weights were changed over to the SWBS classifications as indicated in Appendix A.

The volumes considered relevant to the analysis were those of the deckhouse, hull, and total ship. These volumes were utilized to normalize certain weights into specific weight ratios.

2.2.2 Development of Indices

The functional weights were modified so that the ships are compared on as equal a basis as possible. This modification included the removal of ballast and free flooding liquids, SWBS groups 191 and 198, from the structural weight group, SWBS group 100, and ultimately the light ship weight. Ballast was not included because in a balanced design no ballast is necessary. Also, when a ship has to be ballasted, it tends to increase draft or reduce payload. Therefore, so as not to bias the comparison, ballast was treated as a load and not included in the structural weight group. Similarly, the free flooding liquids, which consist of those liquids in the main condensor, scoop injectors, stern tubes, etc., were excluded from the structural weight group since it was felt they were more appropriately treated as loads. The weight of margins, W_{MR}, was distributed evenly over the light ship weight as was the weight of welding over the structural weight group. The weight of margins was distributed so as not to favor those ships which had not used up their service margins or those in preliminary design with large builder and service margins. The welding weight was distributed to clarify the analysis. The various weight groups were determined as outlined below:

Ballast Weight

$$W_B = W_{191}$$

Free Flooding Liquid Weight

$$W_{FF} = W_{198}$$

Margin Weight

$$W_{MR} = \text{Margins}$$

Light Ship Weight

$$W_{LS} = W_{100}+W_{200}+W_{300}+W_{400}+W_{500}+W_{600}+W_{700}+W_{MR}-W_B-W_{FF}$$

Machinery and Equipment Weight

$$W_{ME} = (W_{200}+W_{300}+W_{400}+W_{500}+W_{600}+W_{700})(1+\frac{W_{MR}}{W_{LS}})$$

Machinery and Equipment Weight Minus Foils

$$W_{MEL} = (W_{200}+W_{300}+W_{400}+W_{500}+W_{600}+W_{700}-W_{567})(1+\frac{W_{MR}}{W_{LS}})$$

Structural Weight

$$W_S = (W_{100} - W_B - W_{FF})(1+\frac{W_{MR}}{W_{LS}})$$

Welding Weight

$$W_W = (W_{197})(1 + \frac{W_{MR}}{W_{LS}})$$

Deckhouse Weight

$$W_{DH} = (W_{150})(1 + \frac{W_{MR}}{W_{LS}})(1 + \frac{W_W}{W_S})$$

Foundation Weight

$$W_{FD} = (W_{180})\left(1 + \frac{W_{MR}}{W_{LS}}\right)\left(1 + \frac{W_W}{W_s}\right)$$

Foundation Weight Minus Foil Support Foundations

$$W_{FDL} = (W_{180}-W_{FS})\left(1 + \frac{W_{MR}}{W_{LS}}\right)\left(1 + \frac{W_W}{W_S}\right)$$

Hull Structure Weight

$$W_H = (W_{110}+W_{120}+W_{130}+W_{140})\left(1+\frac{W_{MR}}{W_{LS}}\right)\left(1+\frac{W_W}{W_S}\right)$$

Hull Plating Weight

$$W_{HP} = (W_{111}+W_{131}+W_{132})\left(1+\frac{W_{MR}}{W_{LS}}\right)\left(1+\frac{W_W}{W_S}\right)$$

Hull Supporting Structure Weight

$$W_{HS} = (W_{116}+W_{117})\left(1+\frac{W_{MR}}{W_{LS}}\right)\left(1+\frac{W_W}{W_S}\right)$$

Miscellaneous Structures Weight

$$W_{MS} = (W_{161}+W_{163}+W_{167})\left(1+\frac{W_{MR}}{W_{LS}}\right)\left(1+\frac{W_W}{W_S}\right)$$

These weight groups are combined into indices, as presented in Table 1, which are employed to determine the impact of those factors which contribute to the increased structural [illegible]ncy of hydrofoils over monohulls. The numerical [illegible] these indices are tabulated in Appendix B.

TABLE 1

STRUCTURAL INDICES

Definition	Name	Units
Δ/∇	Vehicle density	lbs/ft^3
W_S/∇	Vehicle structural specific weight	lbs/ft^3
W_S/Δ	Structural weight fraction	%
W_{DH}/W_S	Deckhouse structural weight fraction	%
W_{DH}/V_{DH}	Deckhouse density	lbs/ft^3
W_{FD}/W_S	Foundation structural weight fraction	%
W_{FDL}/W_S	Foundation less foil impact structural weight fraction	%
W_{FD}/W_{ME}	Foundation specific weight fraction	%
W_{FDL}/W_{MEL}	Foundation less foil impact specific weight fraction	%
W_{MS}/V_H	Miscellaneous structure specific weight	lbs/ft^3
W_H/W_S	Hull structural weight fraction	%
Δ/V_H	Hull density	lbs/ft^3
W_H/V_H	Hull specific weight	lbs/ft^3
W_H/Δ	Hull weight fraction	%
W_{HP}/W_S	Hull plating structural weight fraction	%
W_{HP}/V_H	Hull plating specific weight	lbs/ft^3
W_{HP}/Δ	Hull plating weight fraction	%
W_{HS}/W_S	Hull supporting structure weight fraction	%
W_{HS}/V_H	Hull supporting structure specific weight	lbs/ft^3
W_{HS}/Δ	Hull supporting structure weight fraction	%

Section 2.3 - Comparison of Indices

The various parameters and indices are compared to determine the impact of hydrofoil technology on monohull structures. Trends in the structural weights of the ships considered are analyzed in a first order comparison to determine the relative structural efficiencies. The structural weight is then broken down into key subgroups and analyzed to determine the impact of the factors contributing to the increased structural efficiency in hydrofoils.

2.3.1 Structural Weight

In order to compare the overall structural efficiencies of hydrofoils and monohulls, the vehicle structural specific weights are compared by ploting the structural weight fraction against the vehicle density as noted in Figure 1. This plot is useful in that it highlights the relationship of the structural weight fraction as a function of the vehicle structural specific weight and the vehicle density where:

$$\frac{W_S}{\Delta} = \frac{W_S}{\nabla} \left[\frac{\Delta}{\nabla}\right]^{-1}$$

The vehicle density is a useful indicator of the gross vehicle efficiency whereas the vehicle structural weight indicates the structural efficiency. This plot was first

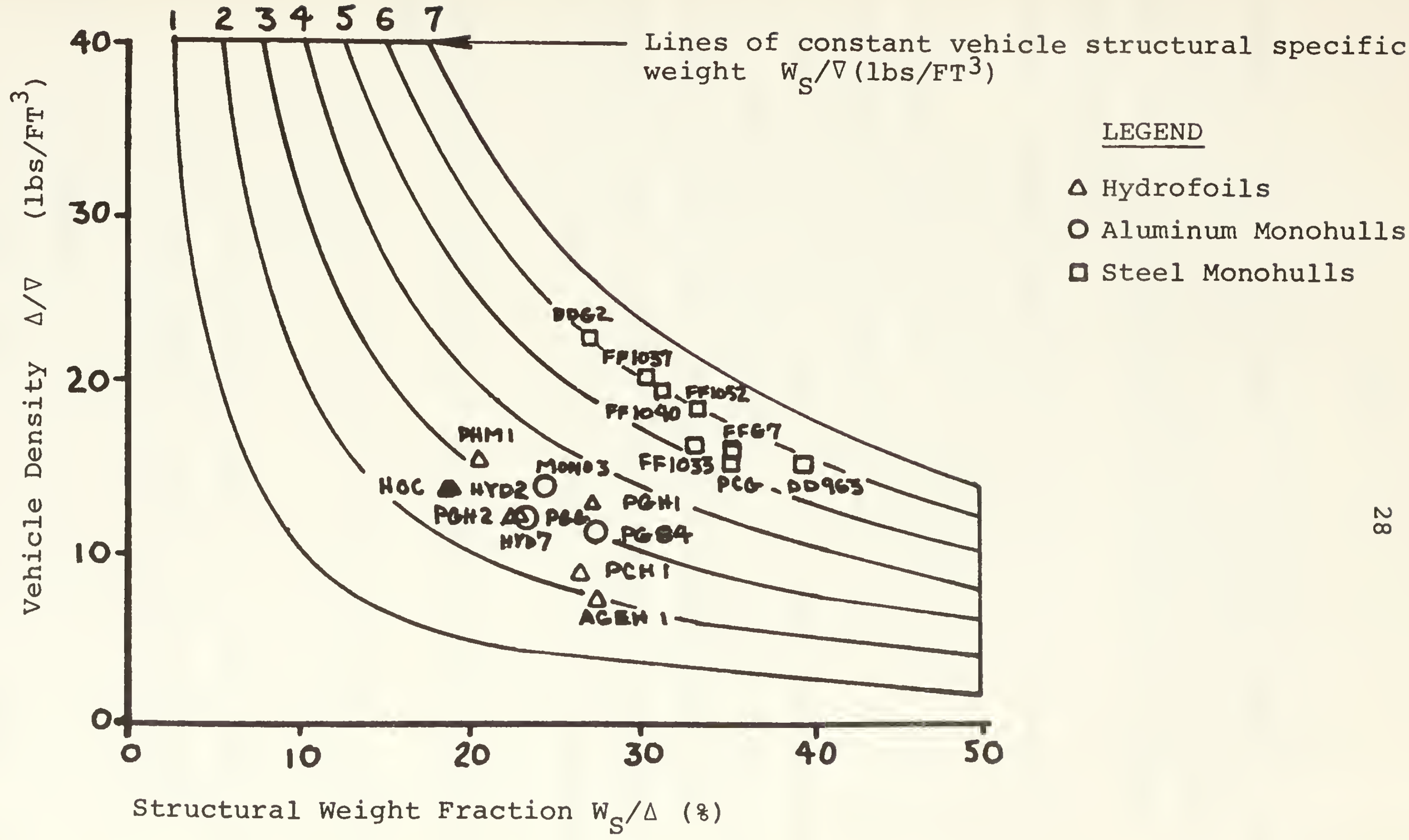


FIGURE 1 - STRUCTURAL WEIGHT TRENDS

introduced by Heller and Clark.[4] Assuming that the vehicle density remains constant, as the structural efficiency increases (i.e., W_S/∇ decreases) the structural weight fraction decreases.

Several observations are in order to put this plot in perspective. First, the steel monohulls vehicle structural specific weight range from 5 to 6 lbs/ft^3 while that of the aluminum monohulls and hydrofoils range from 2 to 4 lbs/ft^3. This is indicative of the impact of the two construction materials. Secondly, even though the material factor is obvious, the impact cannot be properly quantified since the steel monohulls have aluminum deckhouses and associated structures whose weight is included in the structural weight, W_S.

The following conclusions can be made from a review of Figure 1:

- --Aluminum construction leads to higher structural efficiency
- --Aluminum hydrofoils appear to have lower vehicle structural specific weights than aluminum monohulls and thus have a higher structural efficiency
- --The various weight groups which comprise ship structures must be analyzed, to determine accurately the weight impact of aluminum construction.

2.3.2 Deckhouse Weight

Although the deckhouse constitutes only a small part of the structural weight, as indicated below, it affords the opportunity to compare structures of the same material design by the opposing design criteria.

	HYDROFOILS	MONOHULLS
W_{DH}/W_S (%)	6.3 - 14.0	3.6 - 12.3

The PG-84 was not considered since the deckhouse was constructed of fiberglass composite and aluminum. As suggested by Heller and Clark,[4] the deckhouse weight was plotted as a function of deckhouse volume in Figure 2. In reference 19, Mills suggested the following correlation for combatant monohull deckhouses assuming aluminum construction and no allowance for ballistic protection.

$$W_{DH} = 8.57 \times 10^{-4} V_{DH}$$

This trend line was included in Figure 2 as a bench mark.

The wide variance in deckhouse density of the PGH-1 and PGH-2 is of interest since both ships were designed to meet the same performance requirements. Heller and Clark[4] attributed the variance to a difference in design loads but Pieroth[20] felt that the difference was not the design loads,

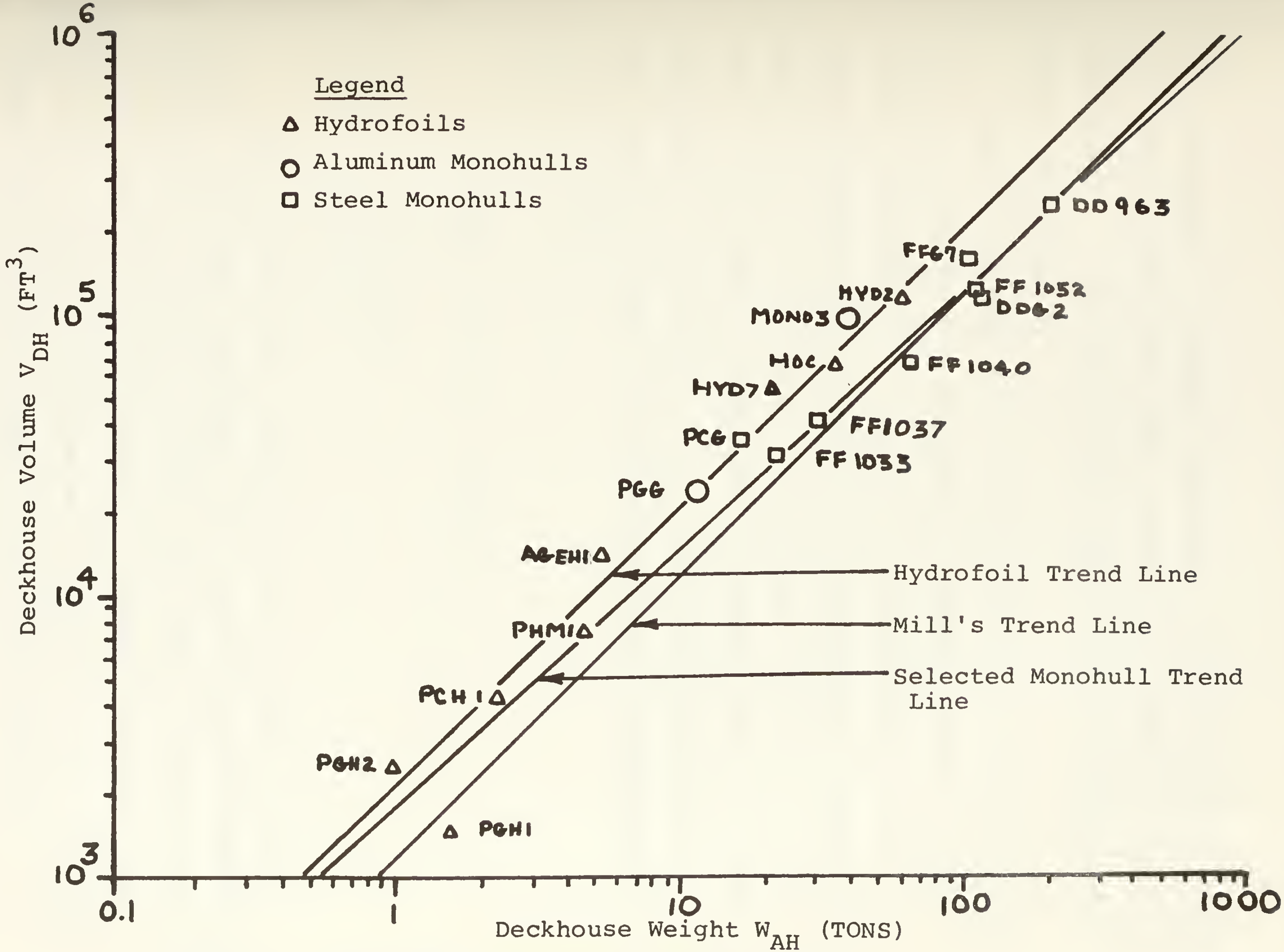


FIGURE 2 - DECKHOUSE STRUCTURAL WEIGHT TRENDS

but the method of analysis employed. He went on to say that the PGH-1 was designed using conventional monohull analysis techniques. It is also of note that the PGH-1 exceeds the Mills trend line.

Trend lines for both the hydrofoils and monohulls were constructed using a least squares linear regression curve fitting technique.[21] The PGH-1 was considered as non-representative and not used in establishing the hydrofoil trend line. To determine the goodness of the fit of the curve to the data, a coefficient of determination, r^2, was calculated. The closer r^2 is to one, the better the fit. The hydrofoil trend line and coefficient of determination are as follows:

$$W_{DH} = 3.76 \times 10^{-4}\ V_{DH}^{1.027}$$

$$r^2 = 0.9871$$

When the hydrofoil trend line was included in Figure 2, it was found that the MONO-3, PCG, and PGG fit the hydrofoil relationship. This was probably the result of the deletion of the nuclear air blast load requirement for these ships. This also reflects a difference in material yield strengths between these ships and some of the other monohulls.

A monohull trend line was then constructed neglecting these points and is as follows:

$$W_{DH} = 2.73 \times 10^{-4} \; V_{DH}^{1.096}$$

$$r^2 = 0.9694$$

When the monohull trend line was included in Figure 2, it was noted that there was a definite difference in the two trend lines indicating that for the same volume, a monohull deckhouse would be heavier than that of a hydrofoil.

In noting the scatter of data for both trend lines the minimum allowable plating thicknesses for part of the ships were obtained.[4,12,13,22,23]

SHIP	PGH-2	PHM-1	AGEH-1	PGG	PCG	DD-963
MINIMUM PLATING THICKNESS	0.10"	0.125"	0.06"	0.25"	0.25"	0.375"

The following observations and conclusions can be made:

--For a given deckhouse volume, a monohull structure will be heavier than a hydrofoil. This is the result of differences in design loads and design criteria. These differences are discussed in Chapters 4 and 5.

--Any differences within the trend line data is the result of differences in design loads, design criteria, material yield strengths, and construction standards and techniques as noted in the cases of the PGH-1, AGEH-1, MONO-3, PCG and PGG.

2.3.3 Foundation Weight

Foundation weight constitutes a small but not insignificant portion of structural weight as indicated:

	HYDROFOIL	MONOHULL
W_{FD}/W_S (%)	10.3 - 15.7	5.9 - 15.7
W_{FDL}/W_S (%)	4.7 - 9.9	

The weight of foundations was plotted versus the weight supported, SWBS groups 200 through 700, in Figure 3, to determine the relative trends. The data was then analyzed, by regression analysis,[21] as discussed in Section 2.3.2, to determine the trend lines listed below.

--Hydrofoils

$$W_{FD} = 6.58 \times 10^{-2}\, W_{ME}^{\;0.99} \quad \text{where } r^2 = 0.9945$$

--Hydrofoils less foil impact

$$W_{FDL} = 2.68 \times 10^{-2}\, W_{MEL}^{\;1.07} \quad \text{where } r^2 = 0.9901$$

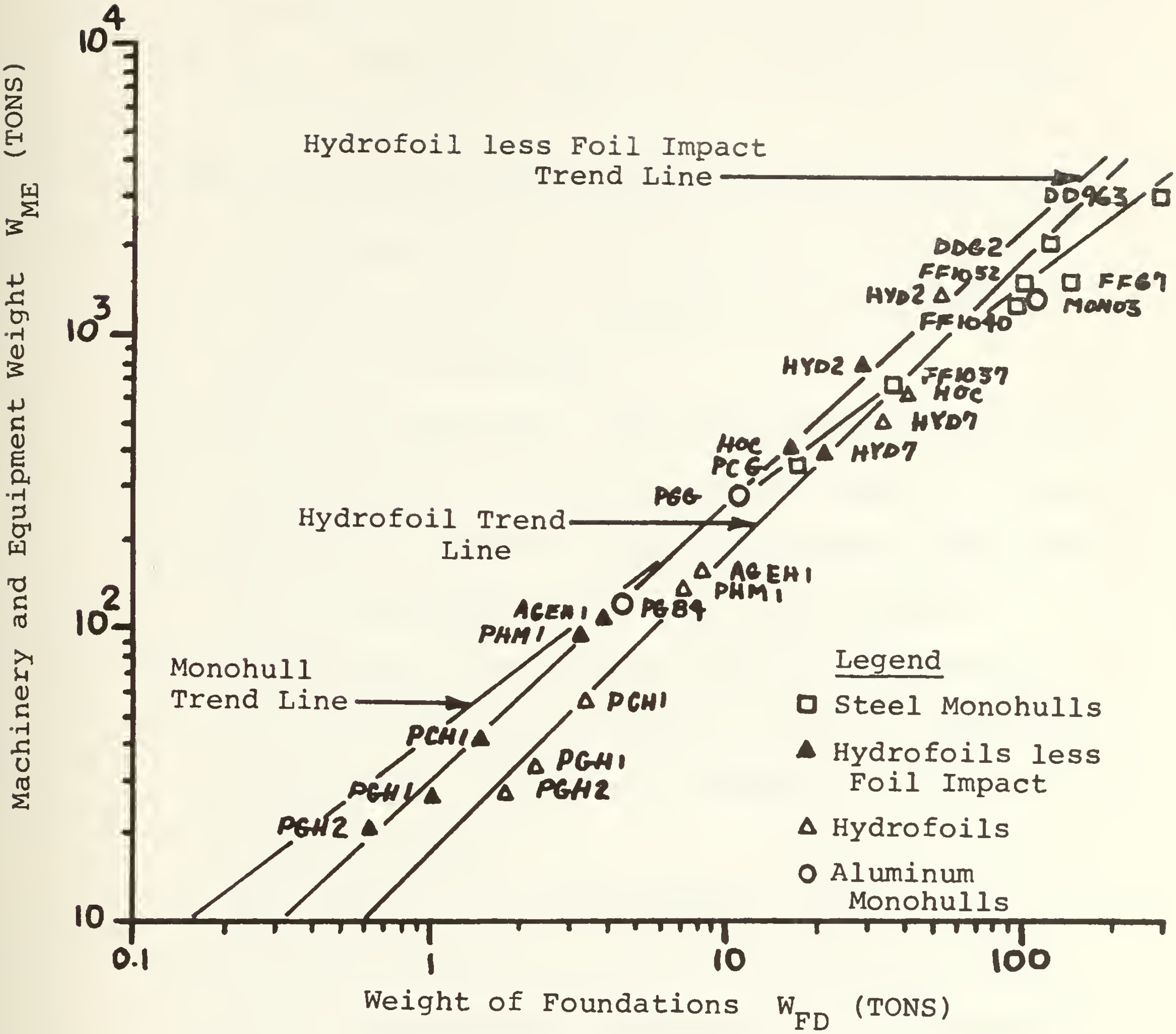


FIGURE 3 - FOUNDATION WEIGHT TRENDS

--Monohulls

$$W_{FD} = 7.60 \times 10^{-3}\ W_{ME}^{1.31} \quad \text{where } r^2 = 0.9641$$

The following observations and conclusions can be made:

--Foil support is an extensive part of hydrofoil foundation weights ranging from 36% to 66% of weight of foundations.

--When the hydrofoil, less foil impact trend line, is compared with the monohull trend line, it is found that as the weight supported increased, the monohull foundation weight for a given weight supported is greater than that of a hydrofoil. This could be indicative of material difference, differences in factors of safety, or different shock standards.

--Hydrofoils have less extensive shafting and reduction gears, but larger prime movers for similar size ships indicating that the foundation weight could also be influenced by the type of weight supported.

2.3.4 Miscellaneous Weight

This weight group was selected to try to quantify both the material impact and design criteria differences. SWBS groups 161, 163 and 167 were considered. This included

castings associated with the installation of the rudder, shafting, anchor, skegs, and stern; sea chests including injection scoop, straines, and overboard discharge; and hull structural closures. The remainder of SWBS group 160 was not considered as well as SWBS group 170 because these weights are primarily a function of the sensor package carried by the ship and not driven by structural consideration. Also, most of these structures would be constructed by similar materials regardless of the vessel type.

The weights of these structures were plotted against the hull volume in Figure 4. This data was analyzed selectively as described in Section 2.3.2 to ascertain the trend lines listed below:

--Hydrofoils less AGEH-1

$$W_{MS} = 3.63 \times 10^{-5} \, V_H^{1.08} \qquad \text{where } r^2 = 0.9667$$

--Steel Hull Monohulls

$$W_{MS} = 2.16 \times 10^{-5} \, V_H^{1.14} \qquad \text{where } r^2 = 0.9076$$

--Aluminum Hull Monohulls

$$W_{MS} = 2.78 \times 10^{-5} \, V_H^{1.12} \qquad \text{where } r^2 = 0.9904$$

The AGEH-1 was not included in the trend line determination since it was non-representative. This is probably due to the construction techniques. The AGEH-1 employed the

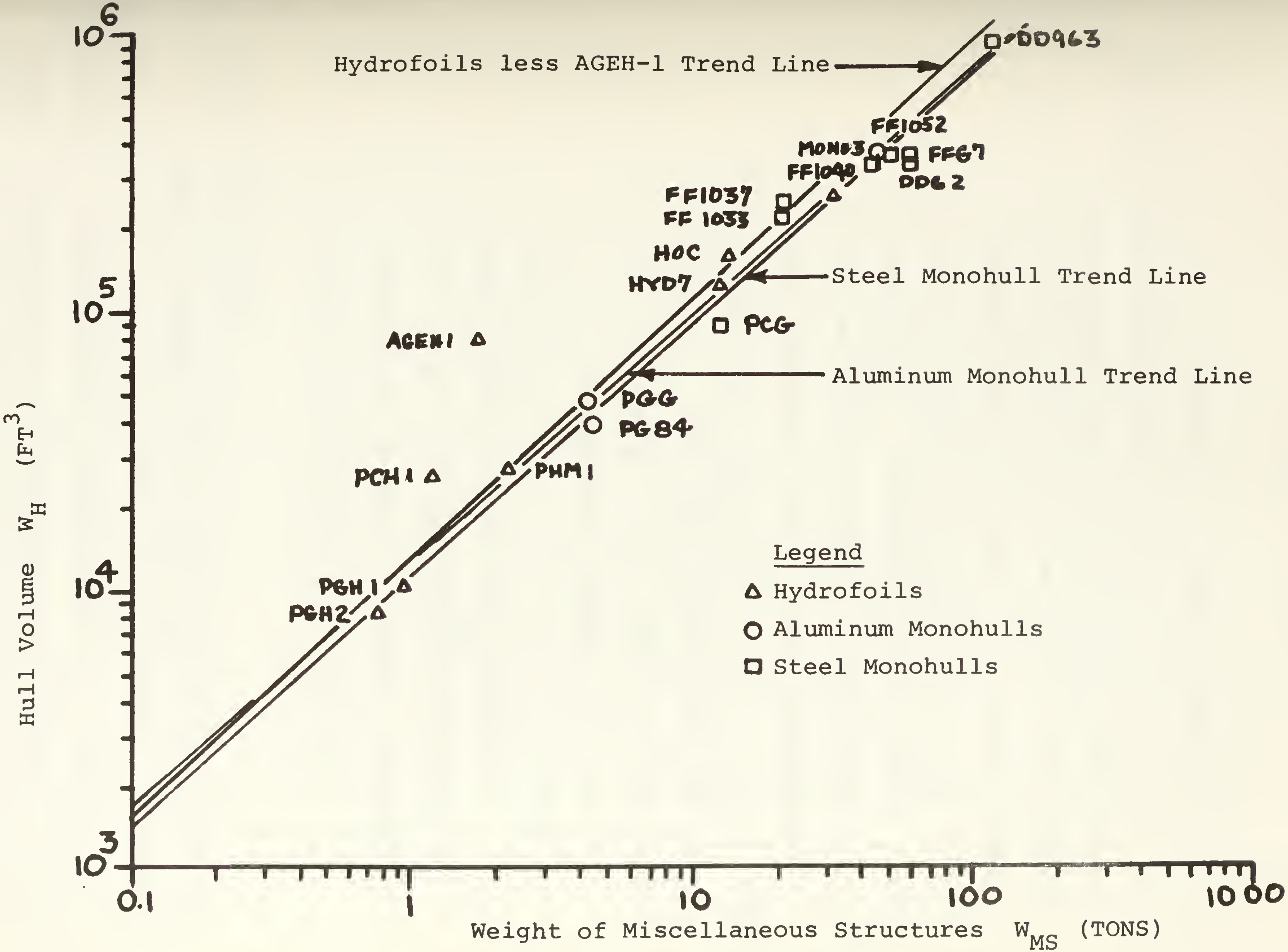


FIGURE 4 - MISCELLANEOUS STRUCTURES WEIGHT TRENDS

milling of various structures to reduce weight.[4] The following observations and conclusions can be made:

--The trend lines for aluminum and steel hull monohulls are very close because the aluminum monohulls are twin screw, twin rudder ships while the steel monohulls are primarily single screw ships. Therefore, if the material impact were neglected, it would be expected that the twin screw ships would have higher miscellaneous weights than single screw ships for equal volumes.

--Similarly, since the hydrofoil does not employ extensive rudders, stern tubes, and sea chests due to its sustension concept, it would be expected that hydrofoils would have lower miscellaneous weights than monohulls.

--Differences in miscellaneous structures are primarily a function of vehicle sustension concept and differences in material.

2.3.5 Hull Weight

The hull weight which is made up of SWBS groups 110, 120, 130, 140 was chosen because it indicates most dramatically the stratification of steel monohulls, aluminum monohulls, and hydrofoils when analyzed and displayed as shown in Figure 5. This plot is similar to Figure 1 except that

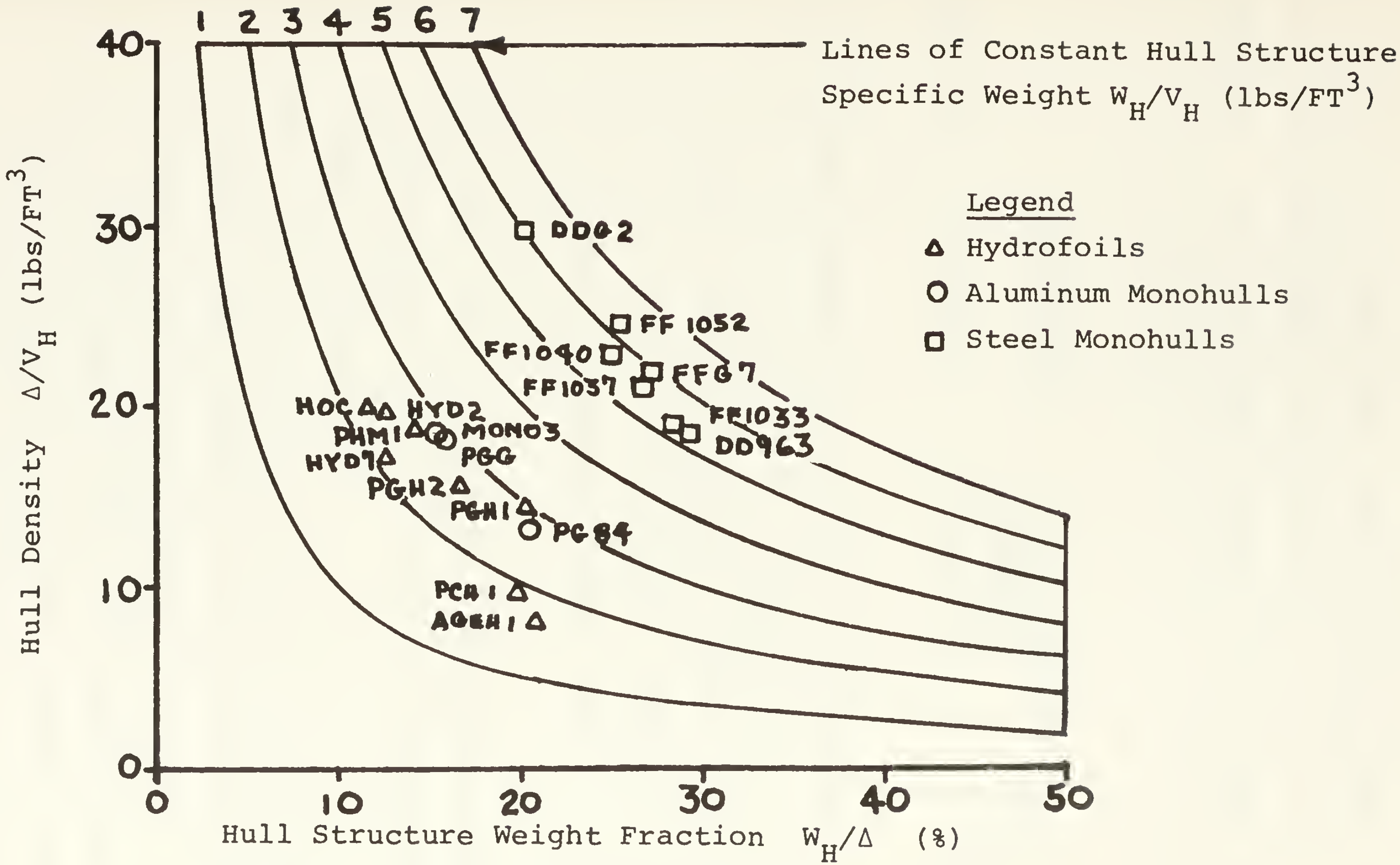


FIGURE 5 - HULL STRUCTURE WEIGHT TRENDS

several weight groups have been deleted and the hull density, the full load displacement divided by the volume of the hull, is considered. The hull weight makes up the largest part of any of the structural groups considered as shown below.

	HYDROFOILS	MONOHULLS	
		Aluminum	Steel
W_H/W_S (%)	57.6-81.5	62.1-74.2	74.0-84.9

The following observations and conclusions can be made:

--The AGEH-1 displays a particularly low hull structure specific weight. This is the result of construction standards and techniques such as low minimum plate thickness and the milling of plating.[4]

--The PGH-1 has a higher hull structure specific weight which is due to the use of conventional design criteria.[20]

--The hydrofoils are structurally more efficient than the steel monohulls having average hull structure specific weights of 2.4 lbs/ft^3 and 5.6 lbs/ft^3 respectively. The aluminum monohulls have an average hull structure specific weight of 2.9 lbs/ft^3. This indicates that the material factor contributes greatly to the structural

efficiency of the hydrofoils but does not account for it totally.

The weight of hull plating and hull supporting structures were identified to determine the allocation of material among the major load bearing elements in the structural system. This effort was carried out in order to determine if a difference in allocation of material between hull plating and supporting structure was employed to reduce structural weight.

2.3.5.1 - Hull Plating Weight

The weight of hull plating, SWBS groups 111, 131, and 132, was considered as shown in Figure 6. The hull density was plotted versus the hull plating weight fraction. The steel monohulls displayed a higher average hull plating specific weight than the aluminum monohulls. This was probably due to the material difference. The aluminum monohulls had higher hull plating specific weights than the hydrofoils. Also, all the monohulls displayed a higher hull plating structural weight fraction than the hydrofoils, as shown below:

	STEEL MONOHULLS	ALUMINUM MONOHULLS	HYDROFOILS
W_{HP}/V_H (lbs/ft^3)	2.80	1.65	1.25
W_{HP}/W_S (%)	29.05	40.75	35.92

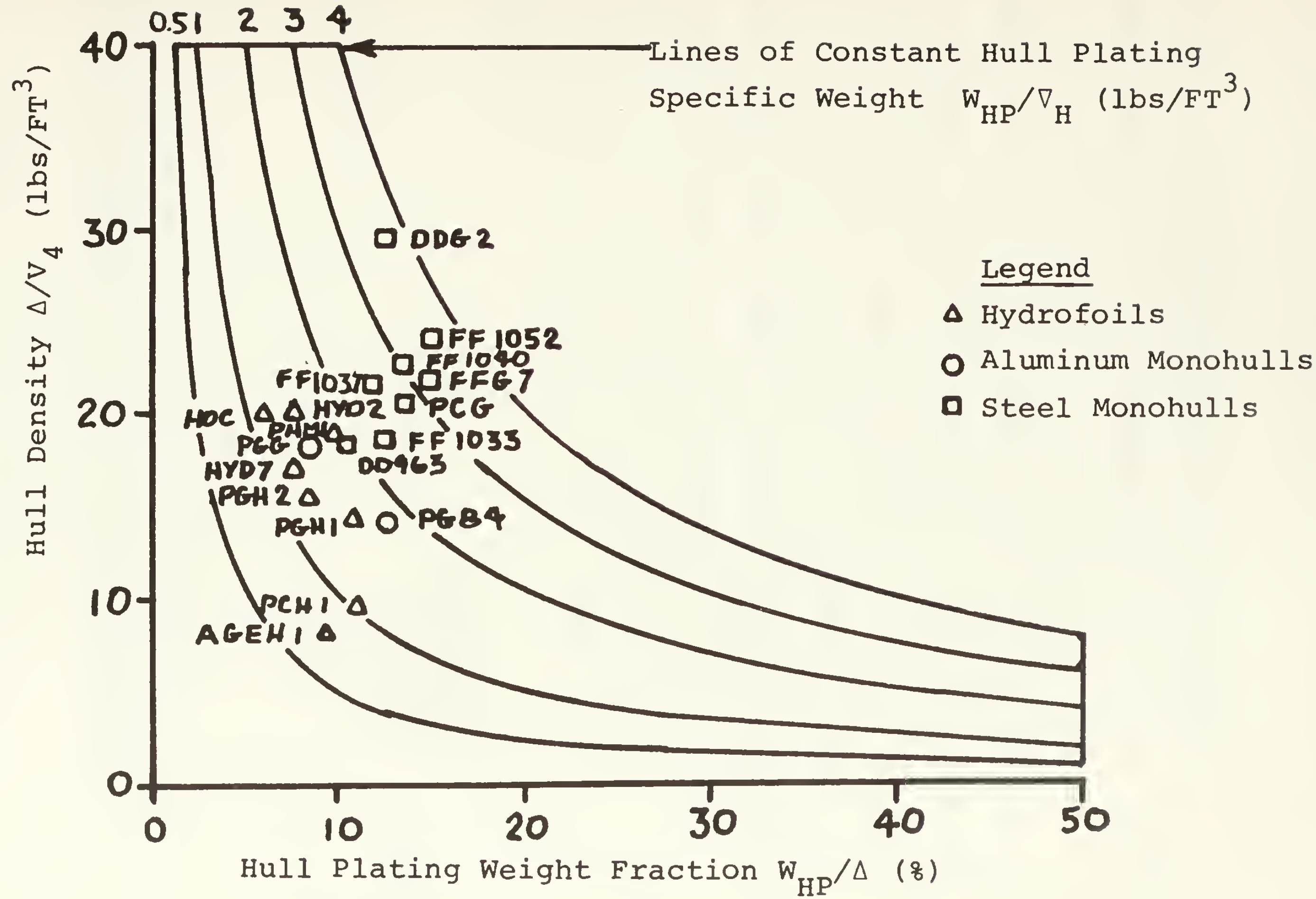


FIGURE 6 - HULL PLATING WEIGHT TRENDS

This indicated that hydrofoils tend to allocate less material to plating than do monohulls.

2.3.5.2 - Hull Supporting Structure Weight

The weight of the hull supporting structure, SWBS groups 116 and 117, was considered as set forth in Figure 7. The hull density was plotted versus the hull supporting structure weight fraction. The steel monohulls had a higher hull supporting structure specific weight than the hydrofoils. However, the aluminum monohulls displayed a lower hull supporting structure specific weight than the hydrofoils. This can be attributed to the impact of the material difference. Also, the monohulls have a lower hull supporting structure structural weight fraction than the hydrofoils, as indicated:

	STEEL MONOHULLS	ALUMINUM MONOHULLS	HYDROFOILS
W_{HS}/V_H (lbs/ft^3)	0.90	0.62	0.70
W_{HS}/W_S (%)	11.72	15.29	20.73

This indicated that hydrofoils tend to allocate more material to supporting structure than do monohulls.

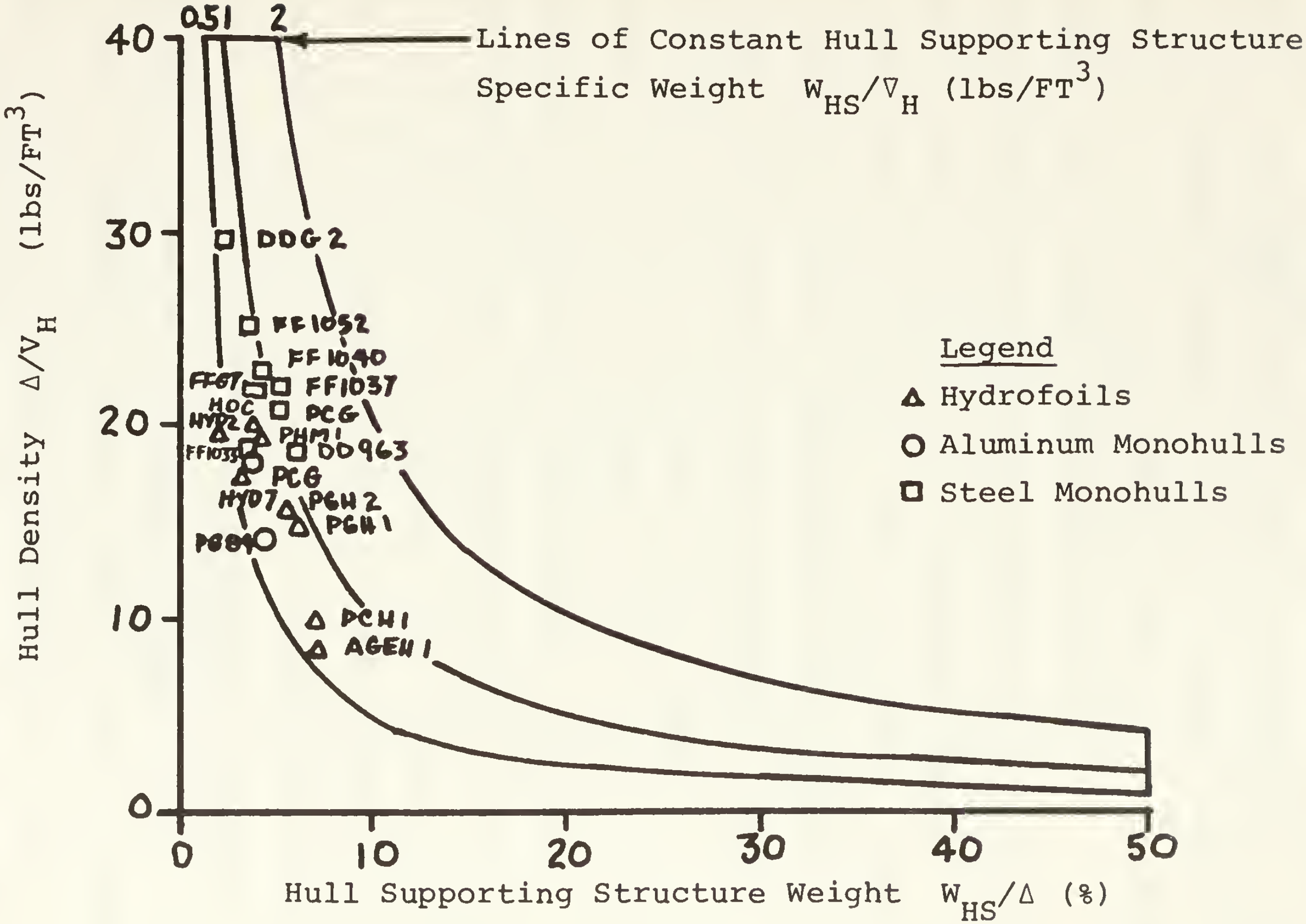


FIGURE 7 - HULL SUPPORTING STRUCTURE WEIGHT TRENDS

2.3.5.3 - Summary and Conclusions

It was concluded, based on Figures 5, 6, and 7, that the superior hull efficiency of the hydrofoils was due primarily to the impact of the material difference. The remaining difference was the result of several factors such as efficiency of structural material allocation, construction techniques, design loads, and design criteria.

The allocation of structural material can affect the hull systems weight such that an acceptable structure can be constructed from less material. The hydrofoils accomplished this by reducing both the longitudinal and transverse spacings below those values normally used in monohulls. However, this reduced weight alternative results in increased cost. This approach was utilized in reference 24 in a study of material and geometrical alternatives for a typical destroyer.

The normalized costs and midship section weights for various combinations of longitudinal and transverse frame spacings resulting from this study for the aluminum alternative are presented in Figure 8. It is noted that as with hydrofoils, monohulls could reduce weight by decreasing frame spacings. However, in monohull design, other considerations such as fendering impacts, better space utilization, and compatibility with bulkhead spacing, which is set by floodable length considerations, have set frame spacings.[25]

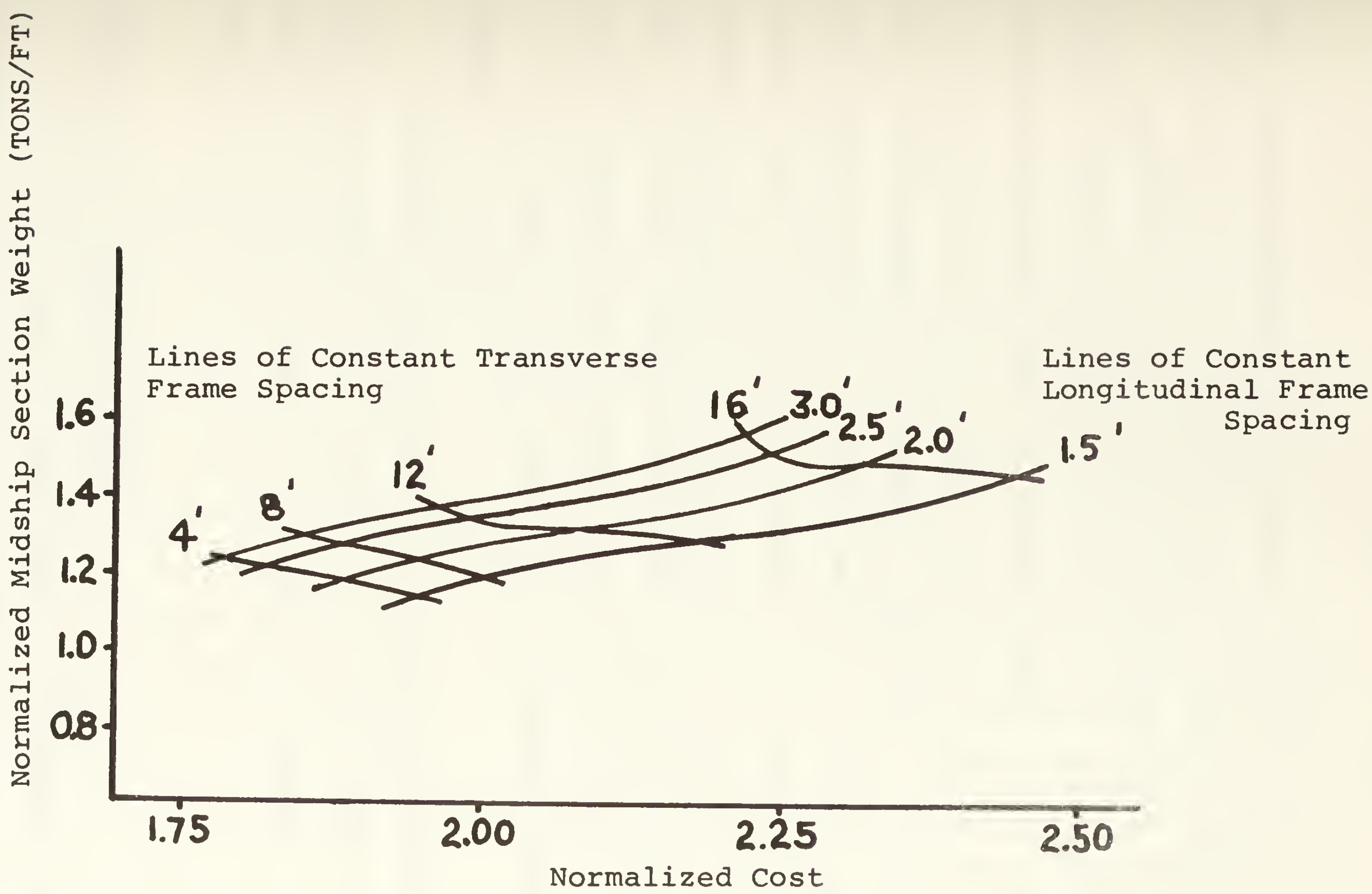


FIGURE 8 - WEIGHT VERSUS NORMALIZED CONSTRUCTION COST FOR TYPICAL DESTROYER

This can be attributed to a lack of priority placed on minimization of structural weight in monohull design.

The hydrofoils utilize various techniques to further reduce structural weight by tailoring the structural system to the anticipated loads. These techniques include the use of lower minimum thicknesses, milling of plating, and the local reinforcement of critical structure. In this manner, the hydrofoil design approach employs a greater depth of design effort in order to decrease the over design or conservatism present in the structural system. Although this will, no doubt, increase the total cost of the ship design, it will decrease the structural weight and underlines the priority placed on the reduction of structural weight in the hydrofoil approach.

The design loads and design criteria differences also affect the superior hull efficiency of the hydrofoils. The impacts of these factors are discussed in depth in Chapters 3 and 4.

Section 2.4 - Material Impact

Since the impact of aluminum construction is the dominate reason for the superior structural efficiency of hydrofoils, the impact of aluminum construction was carried out for five steel monohulls and the resulting indices compared with those of the parent ships.

2.4.1 Weight Impact of Material

The primary material impact parametric model accounts for the weight changes resulting from changing the hull material from steel to aluminum. This model considers the decrease in steel structural weight when changed to aluminum; the increase in ballistic plating to maintain minimum acceptable fragment protection; and the increase in insulation weight to maintain minimum acceptable structural capability under fire conditions.

2.4.1.1 - Structural Weight

The decrease in structural weight can be determined by making the following assumptions:

- --the ship size remains constant and any weight reduction would be allocated to increased payload or the improvement of any other design feature.
- --existing aluminum structure weight remains constant (W_{S-AL}).
- --sonar dome weight remains constant (only effect FFG-7).
- --foundation and miscellaneous structural weight equal to 75% of the original steel weights as assumed in reference 15 (i.e., C = 0.75).

--the weight of hull structure was determined based on a regression analysis of the ships to be redesigned. Those are the FF-1033, FF-1037, FF-1040, FFG-7 and FF-1052. The following relationship resulted

$$W_H = 5.37 \times 10^{-4} [L^2 D]^{0.932} \qquad r^2 = 0.9922$$

Assuming that aluminum ships would follow a similar trend, the following relationship was developed based on MONO-3:

$$W_H = \left[\frac{L^2 D}{L^2 D_{MONO-3}}\right]^{0.932} \qquad W_{H\ MONO-3}$$

Based on the preceeding assumptions, the following relationship was developed for the hull structure impact of changing existing steel structures to aluminum structures, W_{SA}.

$$W_{SA} = W_S - W_{FD} - W_{MS} - W_H + (W_{FD} + W_{MS}) C + \left(\frac{L^2 D}{L^2 D_{MONO-3}}\right)^{0.932} W_{H\ MONO-3}$$

Simplifying, the following is derived:

$$W_{SA} = W_S - (1-C)(W_{FD}+W_{MS}) - W_H + \left(\frac{L^2D}{L^2D_{MONO-3}}\right)^{0.932} W_{H\ MONO-3}$$

and the structural weight reduction due to aluminum, W_{SD}, is

$$W_{SD} = W_S - W_{SA}$$

2.4.1.2 - Ballistic Protection

In order to maintain acceptable fragment protection when changing the hull from steel to aluminum, ballistic plating must be added. Assuming that the weight of ballistic plating or armor is a function of hull volume, the following relationship based on the MONO-3 was developed to determine the weight of armor, W_a.

$$W_A = \left(\frac{V_H}{V_{H\ MONO-3}}\right)(W_{A\ MONO-3})$$

2.4.1.3 - Fire Protection

To maintain existing or, at worst, acceptable structural capability under fire conditions requires the addition of fire retardant insulation to all load bearing surfaces and on all bulkheads around critical spaces. Reference 26 suggested at least one pound per square foot of passive fire protection insulation would be required. Using this as a baseline and considering the MONO-3, HYD-2, and HYD-7 which were built to this standard, it was determined that the following

values for passive fire protection, W_I, could be correlated to the hull volume.

SHIP	MONO-3	HYD-2	HYD-7
W_I (tons)	40.35	30.20	22.62
V_H (ft^3)	366,610	269,020	127,576

Therefore, the following relationship could be determined for passive fire protection based on a least squares linear regression curve fitting analysis.[7]

$$W_I = 4.09 \times 10^{-6} V_H^{1.06} \quad \text{where } r^2 = 0.9982$$

2.4.1.4 - Summary

The relationships developed in the preceeding sections were applied to five monohulls to determine the weight reduction that could be realized by the use of aluminum as a hull material. The monohulls selected were the FF-1033, FF-1037, FF-1040, FFG-7, and FF-1052 since they bracketed the basic design characteristics of the MONO-3 which the impact model used extensively as a base line. The following values were determined:

SHIP	FF-1033	FF-1037	FF-1040	FFG-7	FF-1052
W_{SD} (tons)	261.56	378.39	441.33	517.39	540.01
W_A (tons)	28.25	34.14	44.18	48.49	48.30
W_I (tons)	20.96	26.61	36.83	41.38	41.20

Total Weight Reduction

W_{SDA} (tons)	212.35	317.64	360.32	427.52	450.51
W_{SDA}/Δ (%)	12.00	12.07	10.67	11.86	11.56

By subtracting the weight reduction for aluminum structure, W_{SD}, from the original structure weight, W_S, and adding the ballistic plating, W_A, the weight of an equivalent aluminum structural system, W_{SAL}, can be determined where

$$W_{SAL} = W_S - W_{SD} + W_A$$

Several structural indices are determined and compared with their original values as presented below:

	FF-1033	FF-1037	FF-1040	FFG-7	FF-1052
W_{SAL} (tons)	354.74	464.30	660.79	801.42	802.31
W_S (tons)	588.05	808.55	1057.94	1270.32	1294.02
W_{SAL}/Δ (%)	20.05	17.64	19.57	22.23	20.58
W_S/Δ (%)	33.23	30.72	31.34	35.20	33.20
W_{SAL}/∇ (lbs/ft^3)	3.28	3.51	3.73	3.49	3.74
W_S/∇ (lbs/ft^3)	5.43	6.10	5.97	5.53	6.03
W_{SAL}/W_S (%)	60.32	57.42	62.46	63.09	62.00

These parametrically determined indices were plotted in Figure 9 with the structural indices of the ships previously considered.

The structural specific weights were reduced from an average of 5.81 lbs/ft^3 to 3.55 lbs/ft^3. This is about 73% of the difference of the structural efficiency advantage enjoyed by the hydrofoils.

The following comments and conclusions can be made:

- --Since the payload weight fractions of most destroyers are around 10%[27], the impact of aluminum hull material would be to effectively double the weight fraction available to payload.
- --The parametrically designed aluminum monohull's structural efficiency is markedly increased. They now fall along the trend line of the existing aluminum monohulls. However, there

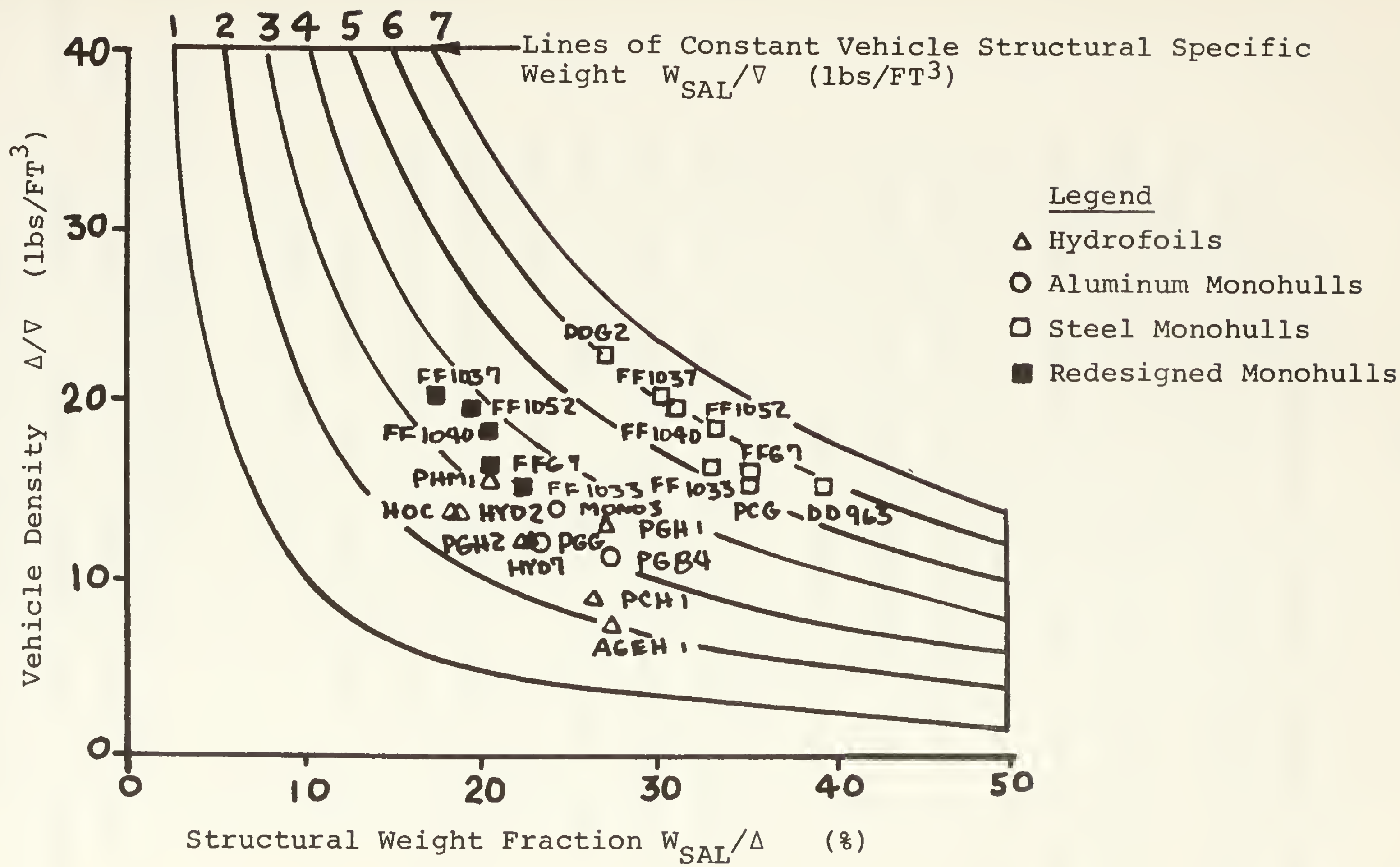


FIGURE 9 - COMPARISON OF REDESIGNED MONOHULLS AND ORIGINAL SHIPS

is still a difference between them and the hydrofoils of about 10 percent which is the result of other factors.

--This analysis is intended for illustrative purposes only and is not exact. The weights included for both ballistic plating and passive fire protection only bring aluminum up to a minimum acceptable performance level and not up to that of steel. Also, it is realized that if the reduction of structural weight were utilized to reduce the size of the ship, the weight reduction would grow due to the spiral effect on powering and fuel, etc. However, since most modern combatants are volume limited, and since structure has no volume associated with it, it is felt that the assumption that the ship size stays constant is justifiable.

2.4.2 Secondary Impact of Material

Although aluminum has the very attractive quality of a reduction in weight, it also has several less attractive qualities. Two of these have already been discussed. Those being poorer performance against fragment projectiles and less than desirable structural capability under fire conditions than steel.

Furthermore, aluminum is more expensive than steel. Two studies, one on a bulk carrier[28] and one on a destroyer,[24] concerning the construction of an aluminum ship predicted the acquisition cost of the structural subsystem would double for an equivalent aluminum hull structure. These two studies highlighted another drawback of aluminum which is an inherent rise in VCG due to a reduction in low ship weight. The study on the bulk carrier[28] indicated a rise in VCG of 5% while the study on the destroyer[24] forcasted a 15% rise in VCG.

Aluminum hulls tend to be more flexible than steel hulls which could result in problems in alignment of propulsion shafting and various weapon systems. This would also lead to higher cyclic loading since transient excitation forces such as whipping would not die out as quickly. The situation is further compounded since aluminum has a lower resistance to fatigue loading than does steel.[29]

2.4.3 Summary

The use of aluminum could reduce the structural weight of a ship as much as 42 %, resulting in a direct savings of 12% of full load displacement. However, the drawbacks associated with the use of aluminum such as increased cost, decreased stability, decreased ballistic protection, decreased structural capability under fire

conditions, and decreased resistance to cyclic loading create some reservations concerning the utilization of aluminum.

Section 2.5 - Summary and Conclusions

The superior structural efficiency of hydrofoils appeared to be primarily a function of material differences. It was found that the utilization of aluminum in monohulls could reduce the structural weight as much as 42%, resulting in a direct savings of 12% of full load displacement. This accounts for 73% of the structural efficiency advantage enjoyed by hydrofoils over monohulls. However, the utilization of aluminum has the associated drawbacks of increased cost, decreased stability and decreased structural capability.

Construction standards and techniques as well as inherent differences in the vehicle concepts such as propulsion systems, sustension systems, and guidance systems, also contributed to the superior structural efficiency of hydrofoils. This contribution was not readily quantified.

Furthermore, hydrofoils employ both a better allocation of load bearing structure between hull plating and hull supporting structure and more detailed design in the tailoring of structure to loads. Both of these tend to increase cost while reducing weights. However, their impact was not readily quantified.

In conclusion, although the factors discussed above account for the majority of the superior structural efficiency enjoyed by hydrofoils over monohulls, further study of both design loads and design criteria was necessary to ascertain their impact.

CHAPTER 3

DESIGN LOADS

To determine the impact of design load differences on structural weight, design load determination procedure and maximum values for both hydrofoils and monohulls are compared in Section 3.1. Some actual measured loads are compared to the design loads in Section 3.2 to determine the relative validity of the two prediction techniques. The phasing of design loads in the design of hydrofoils and monohulls is discussed in Section 3.3 in order to determine which loads govern the design of the various elements of the structural system.

Section 3.1 - Comparison of Design Loads

The design loads determination procedure is compared for those loads experienced in service. The structure affected by each load is listed. The maximum design loads for the PHM-1 and HYD-2, treated as both a hydrofoil and a monohull, are compared.

3.1.1 Determination Procedure

There are several methods for determining hydrofoil loads. Companies and organizations, including Boeing, Grumman, and the U.S. Navy, all employ various yet basically

similar determination methods. The Boeing approach[22,30,31,32] will be analyzed since their procedure was utilized in the design of the majority of the hydrofoils considered in Chapter 2. The design approach considered will follow closely the procedure as practiced in the design of monohull combatants.[23,25,33] The two procedures are set forth in Table 2.

The longitudinal and side bending moment determination for hydrofoils are based on an analytical model describing the bending moment produced on the ship's hull by a variety of loads when the ship broaches in various attitudes. It involves a time dependent computer simulation based on the interaction of the constant loads such as foil drag, strut drag, and the dynamic loads including inertial forces and wave impact. On the other hand, the monohull bending moment design load results from poising the ship on a static wave whose length and height are arbitrary functions of the ships length. The monohull longitudinal bending moment is maximum around midship dropping off to zero at both the forward and aft perpendicular.

Bottom impact pressures, as shown in Table 2, are based on the Von Karmen theory of water impacts on wedge shaped forms. This uses an approximation for water's virtual mass developed by Wagner and Sydow. These equations were modified empirically to give closer agreement with experimental

TABLE 2 - COMPARISONS OF DESIGN LOADS

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Primary Hull Longitudinal Bending Moment	Longitudinally Continuous Hull Structure	Ship is balanced on a static wave at zero speed. Wave is truchodial and has following characteristics: --Wave Height $H_W = 1.1\sqrt{L_{BP}}$ --Wave Profile $X = L_{BP}\frac{\theta}{2\pi} + H_W \frac{\sin\theta}{2}$ $Y = H_W \frac{1-\cos\theta}{2}$ --Longitudinal Bending Moment $BM_x = \int_o^x \int_o^x (b_x - W_x)dx$ where b_x = buoyancy longitudinal distribution of ship when poised on wave. The peak of the wave is located at the ℄ for the "hogging" load condition and the trough is placed at ℄ for the sagging condition. W_x = longitudinal weight distribution of ship	Hullborne: Same as for monohull. Foilborne Calm Water: Ship treated as simply supported overhanding beam supported at foils. Bending moments resulting from hydrodynamic foil loads as transmitted through the foils are superimposed at the foil supports. Foilborne Wave Impact: Involved time dependent computer simulation based on the interaction of the constant loads such as foil drag, strut drag, and the dynamic loads such as inertial forces and wave impact.

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Primary Hull Side Bending Moment	Longitudinally Continuous Hull Structure	Not considered.	Hullborne: Not considered. Foilborne Calm Water: Not considered. Foilborne Wave Impact: Determine in the same manner as for longitudinal bending moment.
Bottom Impact Pressures	Bottom Plating and Framing	Slamming: No established general design loads.	Broaching and Wave Impact: The impact pressures can be determined from the following equations: For $\beta' < 7°$ $P = 0.0217\zeta^2 J[(0.0129-0.1348\beta')\beta'+17.02]$ For $\beta' \geq 7°$ $P = 0.0138\zeta^2 J[(\frac{90}{\beta'}-1)^2 \tan\beta']$ Where $\beta' = \beta-\phi$ $\zeta = V_K \sin\tau' + V_S \cos\tau' + V_o \cos(\tau'-\gamma)$ $V_o = 7.11(H/\sqrt{L})$

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Bottom Impact Pressures (continued)			$L = \pi H/\sin\gamma$ $\tau' = \tau - \theta$ $J = 1.1855 + \sqrt{0.0011715-0.000031\beta}$ and P = average design impact pressure (PSI) ζ = relative normal velocity (fPS) β = local hull deadrise angle (DEG.) ϕ = ship roll angle (DEG.) V_K = ship design foilborne speed (fPS) V_S = assumed sink speed (fPS) γ = wave slope (DEG.) H = design sea state significant wave height (FT) τ = local trim angle (DEG.) θ = ship pitch angle (DEG.)

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Bottom Impact Pressures (continued)			L = wave length such that $\gamma = \tau'$ unless $\tau > 12°$ General Design Values: V_K = 40-50 kts V_S = 5 fPS $\phi = \pm 15°$ $\theta = \pm 3°$ H = 10 FT
Live Loads	Deck Plating and Framing	Static load of stowage weight or concentrated handling loads with the following design minimums: Compartment — Static Load Personnel Spaces, and Passages Main Deck and Above — 75 PSF Living Spaces Below Main Deck — 100 PSF Offices and Control Spaces Below Main Deck — 150 PSF	Static load of stowage weight or concentrated handling loads with a minimum design minimum load of 250 PSF.

TABLE 2 (cont)

DESIGN LOAD	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Live Loads (continued)		Shop Spaces 200 PSF Store Rooms/ Magazines 300 PSF Cargo Stowage and Handling Areas 500 PSF	
Environmental Loads	Side Shell Plating and Framing. Bottom Plating	Passing Wave: Hydrostatic pressure due to passing wave of height. $H_{PW} = DWL + K'\sqrt{L_{BP}}$ K' α ship size K' for small ships = 0.675 K' for large ships = 0.55 Heel: Hydrostatic pressure due to heel of ship ±30° from DWL.	Hullborne: Boarding Water The environmental pressure loads are determined as shown below: $P_{dm} = 105(H)$PSF for main deck aft $L_{BP}/4$ $P_{df} = 1.5(P_{dm})$ for main deck forward $P_{df} = 1.5\ P_{dm} + 64(h-Z)$ for weather-deak above main deck $P_{hm} = P_{dm} + 64(h-Z)$ for $Z \geq h$ but $P_{hm} \geq 250$ PSF for deckhouse except front $P_{hf} = P_{df}$ for front of deckhouse $P_{sm} = 1.5\ P_{dm} - 64Z$ for shell plating aft $L_{BP}/4$
	Weatherdeck Plating and Framing	Green Water: Hydrostatic pressure due assumed submergence of weather-deck by depth H_{GW} at F.P. with head linearly decreasing to mid-ship until reach height of 4' then remain constant over rest of weatherdeck.	

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Environmental Loads (continued)		H_{GW} = 12 FT for cruisers H_{GW} = 8 FT for destroyers and smaller ships	$P_{sf} = 1.5\ P_{dm}$ for shell plating fwd $L_{BP}/4$ to main deck $P_{sf} = 1.5\ P_{dm} + 64(h-Z)$ for shell plating fwd $L_{BP}/4$ above main deck Where h = freeboard from DWL to main deck at lowest point (FT) Z = height above DWL (FT) H = design significant wave height (FT)
	Horizontal Decks Exposed to Weather Deckhouse Sideshell Sideshell above DWL	Weather Loads: --Ice and snow 7.5 PSF --Wind 30.0 PSF --Wind slap 500.0 PSF	
Operational Loads	Subdivision Bulkheads and Vital Space Boundaries	Flooding: Hydrostatic head equal to 4 ft. below the apex of a line from the ship's centerline rising outboard at a 15° slope with the horizontal.	Flooding: Same as Monohull.
	Tank Boundaries	Tank Overfill and Inertial Load: Hydrostatic head to overflow. Do not consider inertial.	Tank Overfill and Inertial Load: Same as Monohull plus inertial load set up when have wave impact or broach.

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Operational Loads (continued)	Designated Deck Sections	Vertical Replishment: 500 PSF	Vertical Replishment: Not established in small ships. Assume same as Monohull used in larger ships.
	Bottom Structure	Drydocking: 20 tons/ft^2 block loading	Drydocking: Not established
Combat Loads	Deckhouse Shell and Framing	Air Blast: Pressure load from nuclear shock front. Specified by Navy when required.	Air Blast: Not considered in small ships. In larger ships assume same as Monohull.
	Structure in Vicinity of Gun	Gun Blast: The pressure due to gun blast is $P = \frac{(200)(1+\cos X)^2}{(R/D)^{1.5}}$ where P = blast pressure (PSI) R = radius vector from muzzle of gun (IN) X = angle between radius vector and gun barrel (DEG.) D = gun calibre (IN)	Gun Blast: $P = P_{(monohull)} \times DMF$ where DMF is dynamic magnification factor DMF = 1.4 for plating DMF = 1.0 for framing

TABLE 2 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULLS	HYDROFOILS
Combat Loads (continued)	Structure in Vicinity of Missile Launcher	Missile Blast: The pressure due to missile blast is: $P = \frac{T(\sin Y + 0.0225/\sin Y)}{A}$ where P = missile blast (PSI) T = total missile thrust (lbs) Y = angle of blast (DEG.) A = area effected (IN^2)	Missile Blast: As specified by manufacturer or test.
	Missile Magazine and Associated Facilities	Accidential Missile Ignition: The pressure due to accidential missile ignition is $P = 2R/A$ where P = accidential missile ignition pressure (PSI) R = burning rate (lbs/SEC) A = total area (IN^2)	Accidential Missile Ignition Not established. Assume same criteria employed.

results.[32] The monohull design load approach does not treat bottom impact pressures formally. The trial and error approach is employed. If a previous design has had problems, the subsequent design's bottom structure scanttings are increased.

Hydrofoil and monohulls use similar approaches for live loads. A minimum static equivalent load is specified based on previous loadings. The hydrofoil approach specifies a single minimum while the monohull approach specifies detailed minimums according to the space. In smaller ships, like patrol boats, monohull designers tend to use the hydrofoil approach of a single minimum static load.

Hydrofoil environmental loads consist of boarding water and are considered for the hullborne case only. This analytical model is based on waves breaking against shoreline structures. Monohull environmental loads are arbitrary standards derived roughly from structural experience.

Operational and combat loads are similar for both hydrofoils and monohulls. The major differences being that hydrofoils consider inertial loadings during wave impact and the inclusion of a dynamic magnification factor, DMF, in the pressure equation for gun blast. The DMF is considered 1.0 for plating and 1.4 for supporting structure. There appears to be no apparent reason for this differentiation.

3.1.2 Maximum Design Loads

The maximum design loads were determined for the PHM-1 which is considered as both a hydrofoil and a monohull. The gross characteristics of the PHM-1 are listed below:

L	116 FT
B	24.5 FT
T	8.5 FT
Δ	240 TONS

Values of the maximum design loads[22] are presented in Table 3.

The HYD-2 was also considered as both a hydrofoil and a monohull to isolate any size difference. The gross characteristics of the HYD-2 are listed below:

L	320 FT
B	51 FT
T	11 FT
Δ	2362 TONS

The numerical values of the maximum design loads[9,25] are presented in Table 4.

TABLE 3 - COMPARISON OF MAXIMUM VALUES OF DESIGN LOADS FOR "HYBRID" PHM-1

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Primary Hull Longitudinal Bending Moment	Longitudinally Continuous Hull Structure	BM_{HOG} = 1675 FT-TONS BM_{SAG} = 1375 FT-TONS	Foilborne Wave Impact BM_{HOG} = 4280 FT-TONS BM_{SAG} = 3595 FT-TONS
Primary Hull Side Bending Moment	Longitudinally Continuous Hull Structure	Not Considered	Foilborne Wave Impact BM_{HOG} = 1700 FT-TONS BM_{SAG} = 1040 FT-TONS
Bottom Impact Pressures	Bottom Structure	Not Considered	Varies - 8928 PSF MAX
Live Loads	Decks	Minimum of 75 PSF to 500 PSF depending on location	Minimum of 250 PSF
Environmental Loads	Bottom Structure	Passing Wave: 1009 PSF at baseline decreasing linearly to 465 PSF at DWL Heel: 552 PSF	
	Sideshell Structure	Wave Slap: 500 PSF from DWL to weather deck	1575 PSF at SWL decreasing to 1050 at weather deck.

TABLE 3 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Environmental Loads (continued)	Hull Weatherdecks	Green Water: 512 PSF at F.P. decreasing linearly to 256 PSF at FWD quarter remaining constant to A.P.	Weatherdecks: Forward FWD Quarter (STA S) 1575 PSF Aft of FWD quarter (STA S) 1050 PSF
	Deckhouse Side Shell	Wind: 30.0 PSF	Front of deckhouse: 1575 PSF at weatherdeck decreasing linearly to 1093 PSF to top. Sideshell of Deckhouse: 1050 PSF at base to 622 PSF at top.
	Deckhouse Weatherdecks	Ice and Snow: 7.5 PSF	Deckhouse Weatherdecks: 622 PSF
Operational Loads	Subdivision Bulkheads and Vital Space Boundaries	Flooding: 497 PSF	Flooding: 497 PSF
	Tank Boundaries	Tank Overfill: 374 PSF bottom structure	Tank Overfill and Inertial Loads: 2630 PSF on bottom structure
	Designated Deck Sections	Vertical Replishment: 500 PSF	Vertical Replishment: 500 PSF
	Keel	Drydocking: 20 $TONS/FT^2$	Drydocking: Not established.

TABLE 3 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Combat Loads	Deckhouse Shell	Air Blast: Not considered on small ship.	Air Blast: Not considered.
	Structure in Vicinity of Gun	Gun Blast: 1440 PSF (avg.)	Gun Blast: 1440 PSF (avg.) - Plating 2160 PSR (avg.) - Support Structure
	Structure in Vicinity of Missle Launcher	Missile Blast: 3500 PSF (avg.)	Missile Blast: 3500 PSF (avg.)

TABLE 4 - COMPARISON OF MAXIMUM VALUES OF DESIGN LOADS FOR "HYBRID" HYD-2

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Primary Hull Longitudinal Bending Moment	Longitudinally Continuous Hull Structure	BM_{HOG} = 29,993 FT-TONS BM_{SAG} = 30,725 FT-TONS	Foilborne Calm Water: BM_{SAG} = 44,100 FT-TONS
Primary Hull Side Bending Moment	Longitudinally Continuous Hull Structure	Not Considered	None when foilborne in calm water
Bottom Impact Pressures	Bottom Structure	Not Considered	Varies - 7200 PSF MAX
Live Loads	Decks	Minimum of 75 PSF to 500 PSF depending on location.	Minimum of 250 PSF
Environmental Loads	Bottom Structure	Passing Wave: 1477 PSF at baseline decreasing to 773 at DWL Heel: 832 PSF	
	Side Shell	Wave Slap: 500 PSF from DWL to weatherdeck	1575 PSF at DWL decreasing to 871 PSF at weatherdeck.

TABLE 4 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Environmental Loads (continued)	Hull Weatherdecks	Green Water: 512 PSF at F.P. decreasing linearly to 256 PSF at FWD quarter remaining constant to A.P.	Weatherdecks: Forward FWD quarter (STA S) 1575 PSF Aft of FWD quarter (STA S) 1050 PSF
	Deckhouse Side Shell	Wind: 30 PSF	Front of Deckhouse: 1575 PSF at weatherdeck decreasing linearly to 1050 at top of deckhouse
	Deckhouse Weatherdeck	Ice and Snow: 7.5 PSF	Side Shell of Deckhouse: 871 PSF at weatherdeck decreasing linearly to 250 PSF at top
Operational Loads	Subdivision Bulkheads and Vital Space Boundaries	Flooding: 768 PSF	Flooding: 768 PSF
	Tank Boundaries	Tank Overfill: Maximum of 960 PSF on bottom structure	Tank Overfill and Inertial Loads: Maximum of 2630 PSF on bottom structure
	Designated Deck Sections	Vertical Replishment: 500 PSF	Vertical Replishment: 500 PSF
	Keel	Drydocking: 20 $TONS/FT^2$	Drydocking: Not established.

TABLE 4 (cont)

DESIGN LOADS	AFFECTED STRUCTURE	MONOHULL	HYDROFOIL
Combat Loads	Deckhouse Shell	Air Blast: 1000 PSF	Air Blast: Not considered
		Gun Blast: 1440 PSF (avg.)	Gun Blast: 1440 PSF (avg.) - Plating 2160 PSF (avg.) - Support structure
		Missile Blast: 3500 PSF (avg.)	Missile Blast: 3500 PSF (avg.)

It would appear, based on Tables 3 and 4, that the hydrofoils are designed to withstand greater loads. As ship size increases, the disparity between the two load profiles decrease but do not converge. This trend is underlined by the ratio comparison of selected hydrofoil to monohull governing design loads for the two "hybrid" ships.

	PHM-1	HYD-2
Longitudinal Bending Moment	2.56	1.44
Bottom Pressure Loading	8.85	4.87
Side Shell Pressure Loading	2.95	2.95
Weather Deck Pressure Loading	3.08	3.08

Assuming that similar design criteria and design methodology are employed, it would be expected that the hydrofoils would have heavier structures. This is exactly the opposite of the trends reflected in the structural weight analysis presented in Chapter 2.

3.1.3 Summary and Conclusions

The design load predictive techniques employed in hydrofoil design are based on an analytical approach. The actual load conditions are simulated mathematically facilitating the determination of maximum equivalent static design loads. The monohull design load approach employs numerous arbitrary techniques for design load predition.

Most of the loads are derived from rule of thumb type criteria which have been proven, or at least not invalidated, through years of all weather structural experience.

Each approach has its individual downfalls. The hydrofoil approach is lengthy and costly, as compared to the monohull approach. However, since design cost is only a small part of the total acquisition cost of a ship, this increase would be considered small. The monohull approach assures no guarantee of structural weight minimization. It compounds conservatism since the designer has no way of knowing what loads the ship will realistically encounter.

It would seem, based on the predictive techniques, that the hydrofoil should experience the greatest loads for similar size ships.

Section 3.2 - Actual and Design Loan Comparison

Data for actual longitudinal bending moments and impact pressures was gathered for hydrofoils and monohulls and compared to the predicted design loads.

3.2.1 Hydrofoils

Very little actual measured load data was available for hydrofoils. The most extensive body of data available was for the AGEH-1.[34] The trial conditions, however, were

much less severe than those the ship would experience in adverse service conditions.

3.2.1.1 - Bending Moment

The maximum longitudinal bending moment occured under test conditions during preplanned broaching in calm sea at 46 kts. The maximum bending moments experienced are as listed below:

BM_{SAG}	BM_{HUG}
2313 FT-TONS	1157 FT-TONS

Although these measured loads are not for the PHM-1, at least they are the same order of magnitude. This lends credance to the hydrofoil load prediction techniques when it is remembered that these measured values are for calm water conditions.

3.2.1.2 - Impact Pressures

The maximum impact pressures occured for the AGEH-1 during broaching in calm water at 37 kts. The maximum dynamic impact pressure was only 8 psi dynamic pressure or 1152 psf. If an average dynamic magnification factor, DMF, of 1.66[35] is assumed to translate this to a static equivalent pressure, it is found that the impact pressure static load would be

1912 psf. This is about 20% of the load predicted by the hydrofoil predictive techniques for the PHM-1. If the maximum impact pressure on the bottom structure of a patrol boat[35] is multiplied by an average DMF,[35] the static equivalent would be 58 psi or 8366 psf. This would indicate that the impact pressures predicted by the hydrofoil approach are reasonable.

3.2.2 Monohulls

The bending moments for several ships were compared with the design bending moments to determine the accuracy of the monohull procedure. Impact pressures actually experienced by monohulls in service were presented to give a feel for the load actually experienced by the bottom structure.

3.2.2.1 - Bending Moment

The peak to peak actual and design longitudinal bending moments are listed in Table 5 for five selected monohulls. These values are plotted versus L^2B in Figure 10. This correlation was suggested by reference 42.

The data contained in Table 4 was fitted to a power curve using a least squares linear regression technique[21] as discussed in Chapter 2. The following trend lines were developed:

TABLE 5 - PEAK TO PEAK LONGITUDINAL BENDING MOMENT COMPARISON FOR SELECTED MONOHULLS

SHIP TYPE	L^2B	DESIGN VALUE (FT-TONS)	REF.	MEASURED VALUE (FT-TONS)	REF.	SEA STATE	SEA HEADING[1]	SHIP SPEED	LOCATION
PG	$6.44x10^5$	$4.81x10^3$	35	$1.05x10^4$	35	6	Head seas	15 kts	----
FF	$6.69x10^6$	$1.11x10^5$	36	$8.80x10^4$	36	6	Bow seas	20 kts	Atlantic
ACR	$9.88x10^6$	$2.03x10^5$[2]	41	$1.23x10^5$[3]	41	6	Head seas	9.5 kts	Mid-Atlantic
DD	$1.13x10^7$	$2.30x10^5$	39	$1.30x10^5$[4]	40	7	Head seas	25 kts	Mid-Atlantic
CV	$6.93x10^7$	$2.25x10^6$	38	$1.23x10^6$	37	7	Bow seas	17 kts	Cape Horn

NOTES:

[1]The heading of the sea is designated by the direction of the sea's motion relative to the direction of the ship's motion (i.e., headseas - 180°, bow seas-135°, beam seas-90°, etc.)

[2]Only the maximum design moment of $1.51x10^5$ FT-TONS hogging was stipulated. The value correlated well with the mariner's design hogging bending moment coefficient, C equal to 29 where BM = $\Delta L_{BP}/C$. Therefore, the mariner's sagging design bending moment coefficient of 85 was utilized to synthesis the peak to peak design bending moment.

[3]The maximum bending moment occurred at 0.40 L_{BP} aft of the F.P. and exceeded the midship bending moment by 30%.

[4]The ship experienced non-structural topside damage when these readings were recorded.

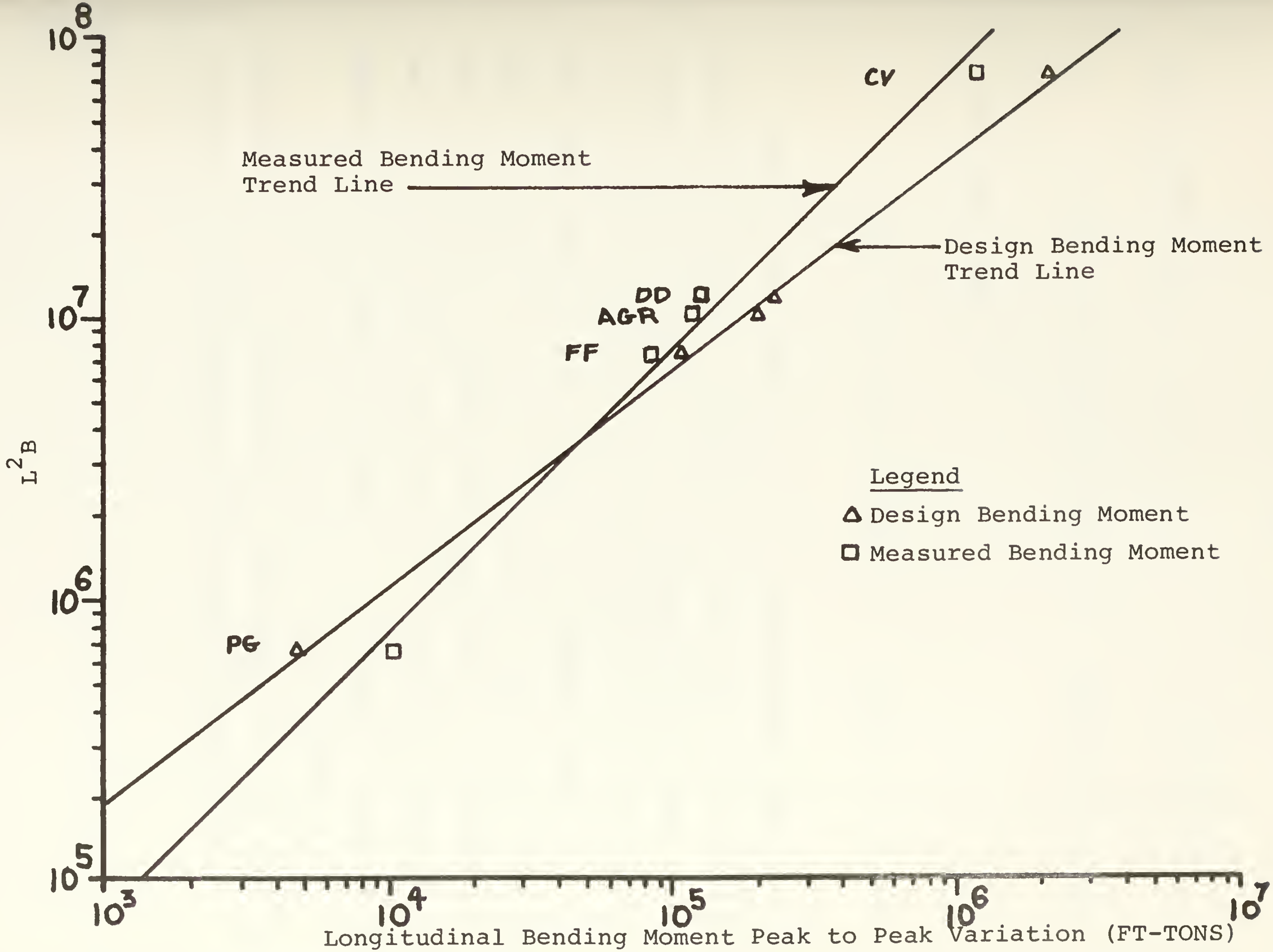


FIGURE 10 - COMPARISON OF ACTUAL AND DESIGN LONGITUDINAL BENDING MOMENTS FOR SELECTED MONOHULLS

DESIGN TREND LINE

$$BM_D = 1.10 \times 10^{-4} [L^2B]^{1.32} \quad \text{where } r^2 = 0.999$$

ACTUAL TREND LINE

$$BM_A = 1.31 \times 10^{-2} [L^2B]^{1.00} \quad \text{where } r^2 = 0.988$$

Based on the coefficients of determination, the trend lines were judged to adequately fit the data. If a length to beam ratio of about 8.75 is assumed and the trend lines are equated to determine the approximate value of L where the design bending moment and actual bending moment are equal, a length L of 300 ft. is found. This would indicate that for ships of lengths less than 300 ft., the monohull design bending moment determination procedure underpredicts; and for ships greater than 300 ft. in length, it overpredicts.

This is a logical eventuality if the probability of excedence of the maximum design wave height, Hw, as outlined in Table 2, is considered for the North Atlantic.[42]

SHIP	Hw(FT)	Exceedence Probability (%)
PG	13.66	50
300' SHIP	19.05	26
FF	21.72	20
AGR	22.44	18
DD	24.00	15
CV	31.50	6

It is noted that the smaller ships have a greater chance of encountering waves larger than their maximum design wave height than do the larger ships.

It was noted that when the PG exceeded its design bending moment by roughly twice the value, no structural damage was experienced.[35] Conversely, a CV experienced structural damage even though the design bending moment was not exceeded.[37] Comparing structural experience and accuracy of bending moment prediction, it would appear that the correct prediction of bending moment does not insure structural survivability. This is probably the result of inaccurate prediction of secondary loads or underprediction or overprediction of structural strength as governed by the design criteria and methodology. Also, the CV was older and could have failed due to cyclic loading or fatigue. The design criteria and methodology are discussed in depth in Chapter 4.

3.2.2.2 - Impact Pressures

Impact pressures experienced by two monohulls in service conditions are listed below:

SHIP	REF	STATIC IMPACT PRESSURES	SEA STATE	SEA HEADING	SHIP SPEED
PG	34	8252 PSF	6	Head	15
DD	40	6048 PSF	7	--	--

Although monohulls do not design for bottom impact pressures but rely instead on previous design experience, it appears impact pressures are significant and should be considered. It is also of interest that the impact pressures experienced by the monohulls are around the values prededicted for the equivalent sized hydrofoils in Tables 3 and 4.

3.2.3 Summary and Conclusions

The following observations and conclusions can be made:

--Although the actual load data available for hydrofoils was inadequate, it seemed to lend credance to the predictive technique. However, no quantitative conclusions are justifiable.

--The monohull inaccurately predicts design loads both underpredicting and overpredicting the actual values.

--Thus no conclusions can be drawn on comparisons of actual loads of monohull and hydrofoils.

Section 3.3 - Design Loads Phasing

The load phasing approach of the hydrofoil and monohull design procedures were considered and the governing loads and structure affected set forth.

3.3.1 Hydrofoils

All three load conditions, namely, foil borne in calm water, foil borne with wave impact, and hull borne, are considered in hydrofoil design to determine the load condition that governs the design of each structural element. All loads are considered at maximum design values. Only combat loads are coupled with other loads.[30] Different parts of the structure are designed based on different load conditions as indicated for a typical hydrofoil below:

STRUCTURE	LOAD CONDITION	GOVERNING LOAD	COMBINED LOAD
Bottom Structure	Foilborne Wave Impact	Wave Impact	None
Main Deck	Hullborne	Boarding Water	Combat Loads
Tank Boundaries	Foilborne Wave Impact	Fuel Inertia	NOne
Deckhouse	Hullborne	Boarding Water	Combat loads
Keel	Foilborne Wave Impact	Wave Impact	NOne
Side Shell	Hullborne	Boarding Water	None

3.3.2 Monohulls

In monohull structural design, certain loads are considered as acting together. These are longitudinal bending moment and secondary loads, such as live loads, environmental loads, and tank overfill. Slamming, flooding, drydocking, and combat loads are considered as acting as individual loads. All loads are considered to act at maximum design values.[12] As in hydrofoil design, different parts of the structure are designed based on different governing loads as indicated below for a typical monohull.

STRUCTURE	GOVERNING LOAD	COMBINED LOAD
Bottom Structure	Longitudinal Bending	Passing Wave
Main Deck	Longitudinal Bending	Green Water
Tank Boundaries	Tank Overfill	None
Deckhouse	Air Blast	None
Keel	Drydocking	None
Side Steel	Wave Stop	Longitudinal Bending

3.3.3 Summary and Conclusions

Loads are phased differently for hydrofoils and monohulls and this clouds the issue. The design loads are combined within the framework of stress analysis. Therefore, the opposing design criteria and methodology must be considered to gain insight into the relative design loads ranking.

Section 3.4 - Summary and Conclusions

Hydrofoil load criteria is based primarily on analytical techniques as modified to match experimental evidence. Monohull load criteria is based on general design load criteria derived roughly from service experience.

Due to a lack of actual load data, the hydrofoil design load predictive techniques could not be adequately verified. It was found that the monohull design load predictive technique underpredicts for small ships and overpredicts for large ships. No conclusions could be made concerning the ranking of actual loads experience by monohulls and hydrofoils.

Based on a comparison of predicted loads, according to both techniques, for a 240 ton and 2400 ton ship, it was found that hydrofoils are designed for higher loads. Therefore it follows that hydrofoils do not have higher structural efficiency due to lower design load. In fact, just the opposite would be true.

CHAPTER 4

DESIGN METHODOLOGY AND CRITERIA

The design methodology and criteria of hydrofoils and monohulls are compared to determine the relative impact on structural weight. Nomenclature is standardized whenever possible to facilitate comparison. Only normal stress criteria is considered since they normally are the controlling stresses in hull structural design. In Sections 4.1 and 4.2 the design methodology and criteria of hydrofoils and monohulls, respectively, are outlined. In Section 4.3, structural elements in a hydrofoil and a monohull are compared in order to determine the stress levels or factor of safety of the structural elements at maximum design load.

Section 4.1 - Hydrofoils

The structural systems of hydrofoils are designed to be capable of surviving the maximum design loads. The ship's structure is broken down into individual elements. A structural element is chosen and subjected to the allowable stress criteria for each mode of failure. This process is iterated until a suitable structural element is found that satisfies all the allowable stress criteria.

Each element is assumed to act as simplified structural models for the various modes of failure. These simplified structural models take the form of beams and columns which are subjected to various support constraints and thick or thin plates under lateral loading. Design curves, based on experimental evidence, are employed to determine the various allowable stresses and plate thicknesses. Selected design curves are included in Appendix C. In hydrofoils, heavily loaded plates, such as bottom structure, are designed based on thin plate analysis while normally loaded plates are designed using the thick plate design curves.

The maximum design load is assumed to be distributed over the entire structural element under consideration as indicated in Figure 11.[30] The stress can then be calculated based on the specific material and specific mode of failure.

After all the individual structural elements are designed, the logitudinally continuous material, the hull girder, is analyzed as a simple beam to determine its ability to withstand failure when subjected to the design longitudinal and side bending moments.

$w = PS$ | Assumes full fixity of framing at supports

$V = 3/8\ w\ell$

$M_{support} = -0.0742\ wL^2$

$M_{on\ a\ span} = 0.0404\ wL^2$

where

P = pressure load

S = Longitudinal spacing or effective width of plating

where $W_c = 1.7\ \sqrt{E/\sigma_{cy}}$

ℓ = Frame spacing

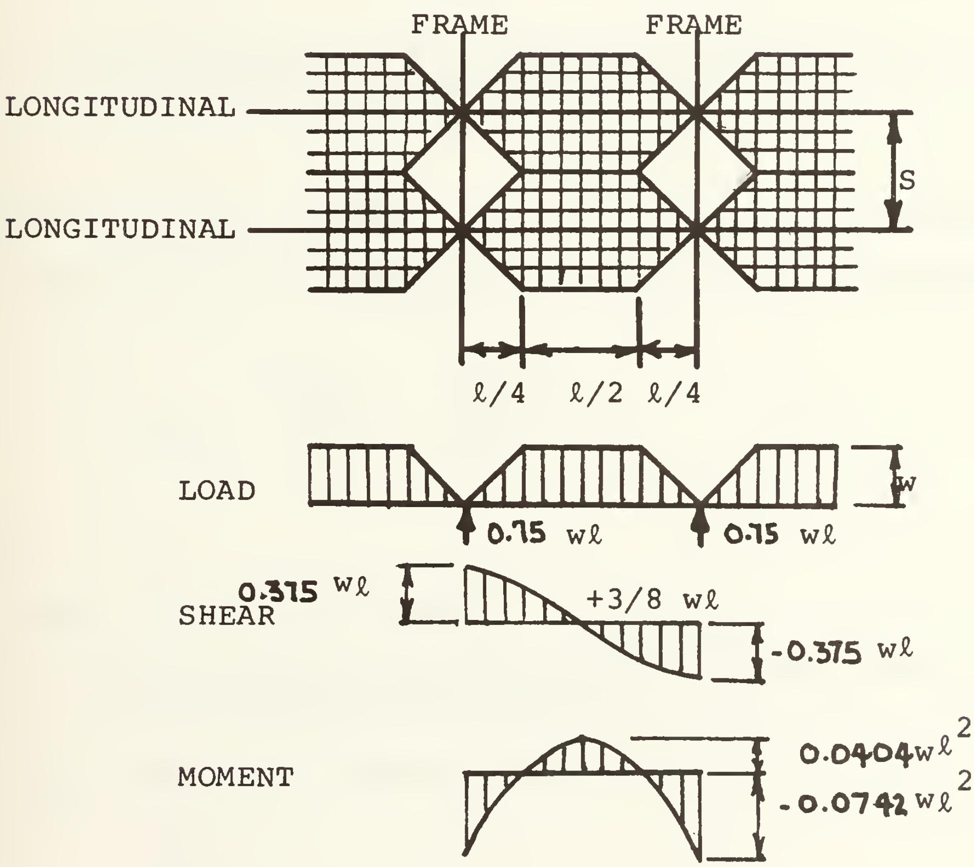


FIGURE 11 - HYDROFOIL DESIGN LOAD DISTRIBUTION

In the above cases, except for plating, the simple beam analogy is ulitized as developed below.

$$\sigma_{CALC} = \frac{MZ}{I}$$

where

σ_{CALC} = Calculated stress in the structural element under consideration

BM_L = Longitudinal bending moment the structural element is subjected to

I_{yy} = Moment of inertia of the structural element about y axis

Z = the distance of the structural element from the neutral axis in z direction

In the case where combined bending is present, the simple beam analysis can be extended to include both as follows:

$$\sigma_{CALC} = \frac{BM_L \; Z}{I_{yy}} + \frac{BM_S \; Y}{I_{zz}}$$

where

BM_S = Side bending moment

Y = The distance of the structural element from the neutral axis in y direction

I_{zz} = Moment of inertia about the z axis

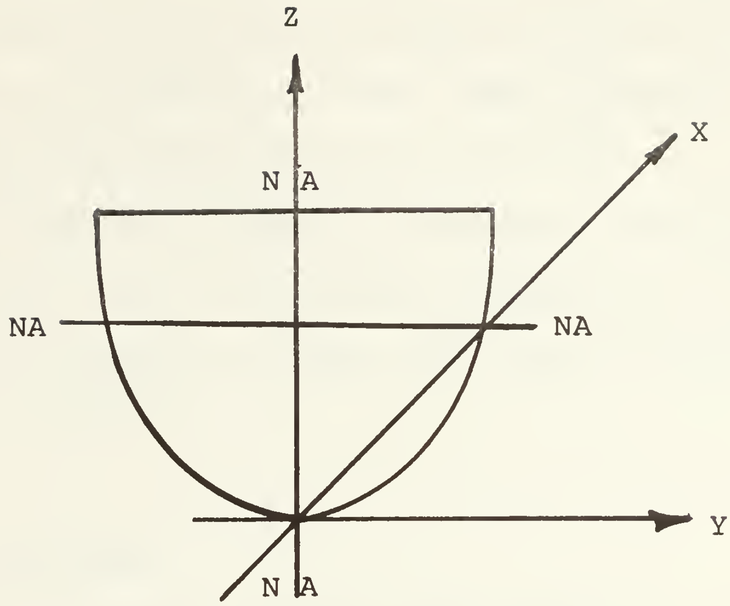


FIGURE 12 - STRUCTURAL ELEMENT SECTION GEOMETRY

For hydrofoils, the allowable stress, σ_{ALL}, is specified for various modes of failure as:

$$\sigma_{ALL} = \text{lower of } \left[\begin{matrix} \sigma_u/1.5 \\ \sigma_y \end{matrix} \right]$$

where

σ_u = the stress resulting from the maximum load the structural element can take without gross failure (i.e., large deformations are allowed)

σ_y = the stress resulting from the maximum deformation that can be allowed without detriment to safe operation

This indicates that hydrofoils employ a safety factor of 1.0 in the case of yield failure and a safety factor of 1.5 in the case of ultimate failure. Some hydrofoil designers have employed yield factors as high as 1.2.[9]

A table of allowable material properties and empirical design curves for specific structural elements for the determination of allowable ultimate and yield stresses are included in Appendix C.

Section 4.2 - Monohulls

In monohull structural design the approach is basically the same as that utilized in hydrofoils except that a heirchy of stress is developed. The stresses are divided into primary stresses σ_1 and secondary stresses σ_2 where:

σ_1 = stress in a structural element due to longitudinal bending moment

σ_2 = stress in a structural element due to local loadings

The primary stress distribution assumed in a ship's cross section due to primary longitudinal bending is as shown in Figure 13. The difference in the assumed distribution for inner structure and the outer shell, at the neutral axis, is probably due to vertical bending in the side shell resulting from compression of the ship's cross section during longitudinal bending.

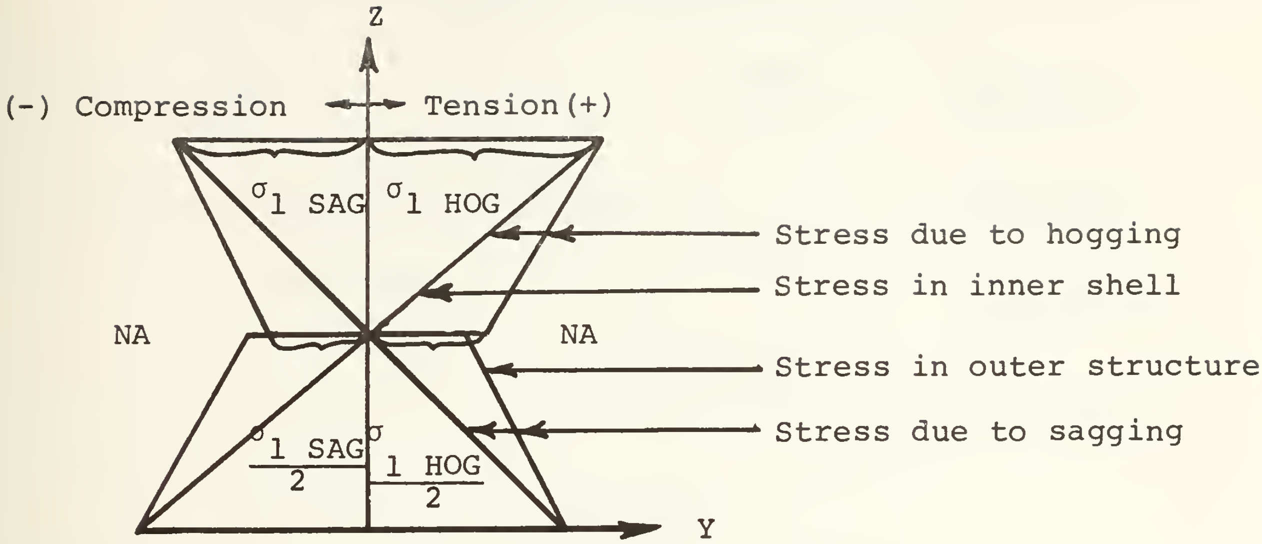


FIGURE 13 - MONOHULL ASSUMED PRIMARY STRESS DISTRIBUTION

The monohull design approach, as in the hydrofoil approach, assumes that each element acts as a simplified model, such as a beam or column, subjected to various support constraints. The monohull approach only employs thick plate analysis. In the monohull approach this has been reduced to an arbitrary equation which includes several discrete constraints for various types of plating as outlined in Table 6. This equation yields the minimum allowable plate thickness, t.

TABLE 6

MINIMUM MONOHULL PLATING THICKNESS

$$t = b\frac{K_t\sqrt{H}}{C_t}$$

C_t & K_t = empirical constants such that

where: t = plating thickness

b = short side of panel

H = seawater hydrostatic head

a = long side of panel

C_t Values

Application	MS	HTS	HY80	HY100	5456 Al
	Material				
Plating exposed to sea action such as shell above a line 2 ft below the full load waterline, weather decks, superstructure, or where deformation would interfere with operation of attached equipment	350	400	500	550	300
Boundaries of tanks and shell below a line 2 ft below the full load waterline, and normally floodable voids	550	630	750	800	470
Main subdivision bulkheads, damage control deck, and boundaries of vital spaces	700	800	900	1000	600

TABLE 6 (cont)

K_t Values

Ratio b/a	K_t
0.5 or less	1.00
0.6	0.98
0.7	0.94
0.8	0.89
0.9	0.84
1.0	0.78

The monohull approach employs a different load profile from that of the hydrofoil. The monohull load profile assumes different support constraints for different types of loads. This is reduced to an equation similar to that used by hydrofoils but with different constants for different type loads as shown in Table 7.

TABLE 7

MONOHULL DESIGN LOAD DISTRIBUTION

$w = PS$

$M = wL^2 \ C_L$

where

P = Pressure load

S = Longitudinal spacing or effective width of plating

where $W_c = 2 \sqrt{E/\ _y}\ t$

w = Distributed design load

ℓ = Frame spacing

C_L = Support constraint coefficient as a function of different loads

	C_L Values	
DESIGN LOAD	MIDSPAN	SUPPORT
Hydrostatic Pressure-even spacing	.0417	.0833
uneven spacing	.0625	.100
Live Load	.0833	.100

The major difference between the monohull and hydrofoil design methodology is that primary logitudinal bending stresses are combined with selected secondary stresses as specified by the specified failure mode criteria listed below:

--Tension critical structures

$$\sigma_{AT} + \sigma_{ST} \leq \sigma_{ALL}$$

--Compression critical supporting structure

$$\frac{\sigma_{AC}}{K\sqrt{C}} + \frac{\sigma_{SC}}{\sigma_{ALL}} \leq 1.0$$

--Compression critical plating

$$\sigma_{AC} + \sigma_{SC} \leq 0.80\ \sigma_{UP}\ \frac{\sigma_{C}}{\sigma_{YM}}$$

where

σ_{AC} = Maximum compressive stress due to either primary longitudinal bending or local axial forces

σ_{AT} = Maximum tensile stress due to either primary longitudinal bending or local axial forces

σ_{ALL} = The material design allowable stress

σ_{C} = Allowable column stress of supporting structure

σ_{SC} = Maximum compressive stress due to local secondary loading

σ_{ST} = Maximum tensile stress due to local secondary loading

σ_{UP} = The ultimate allowable compressive stress of plating

σ_{YM} = The material yield strength

K = Design constant whose discrete value is based on the slenderness ratio, ℓ/R, of the supporting structural element. The values of K are outlined below:

$\ell/R \leq 60$ K = 0.80

$\ell/R \geq 60$ K = 0.67

ℓ = The length of the supporting structure. This is usually considered to be the transverse frame spacing.

R = The radius of gyration of the supporting structural cross section

The material design allowable stress, σ_{ALL}, has evolved over the years for the various materials. The allowable stress for the various steels are based generally on the following equation.[23]

$$\sigma_{ALL} = \frac{1}{2}\left(\frac{\sigma_{UM}}{2.15} + \frac{\sigma_{YM}}{1.25}\right)$$

where

σ_{UM} = The material ultimate strength

On the other hand, the allowable stresses for the various aluminums are determined as a function of the yield strength of the material in the heat affected zone resulting from welding.[23] The values for the allowable stresses and yield stresses are included in Appendix C.

After the individual members are designed, the hull girder is analyzed as a simple beam and varified as meeting the following criteria.

$$\sigma_1 \leq \sigma_{1A}$$

Where σ_{1A} is the maximum allowable primary longitudinal bending stress, values for the allowable primary bending stress are listed for various materials.

	HY80	HTS	MS	AL
σ_{1A} (PSI)	23,500	21,300	19,000	10,000

If the maximum primary stress calculated is greater than the allowable stress, the hull girder is strengthened to reduce the maximum primary stress. This is normally accomplished by adding material to the main deck plating and the bottom plating.

The individual structure affected by combat, flooding, and drydocking loads are analyzed and varified according to the above stress criteria. However, it is assumed that no other loads are present and that these loads act individually.

The monohull allowable stress criteria is based on arbitrary extrapolations of experience determined acceptable stress levels. Therefore, straight forward safety factors

cannot be readily identified. However, it can be stated that monohull criteria utilizes larger safety factors for allowable ultimate stress levels than for yield stress levels as do the hydrofoils. If longitudinal bending stress is considered as ultimate loading, an ultimate factor of safety can be determined by dividing the material yield stress, σ_{YM}, by the allowable primary longitudinal bending stress, σ_{1A}, as follows:

	HY-80	HTS	MS	AL(5456)
ULTIMATE SAFETY FACTOR	3.40	2.11	1.74	2.60

If the total stress level is considered as a yield loading, a yield factor of safety can be determined by dividing the material yield stress, σ_{YM}, by the allowable stress, σ_{ALL}, as follows:

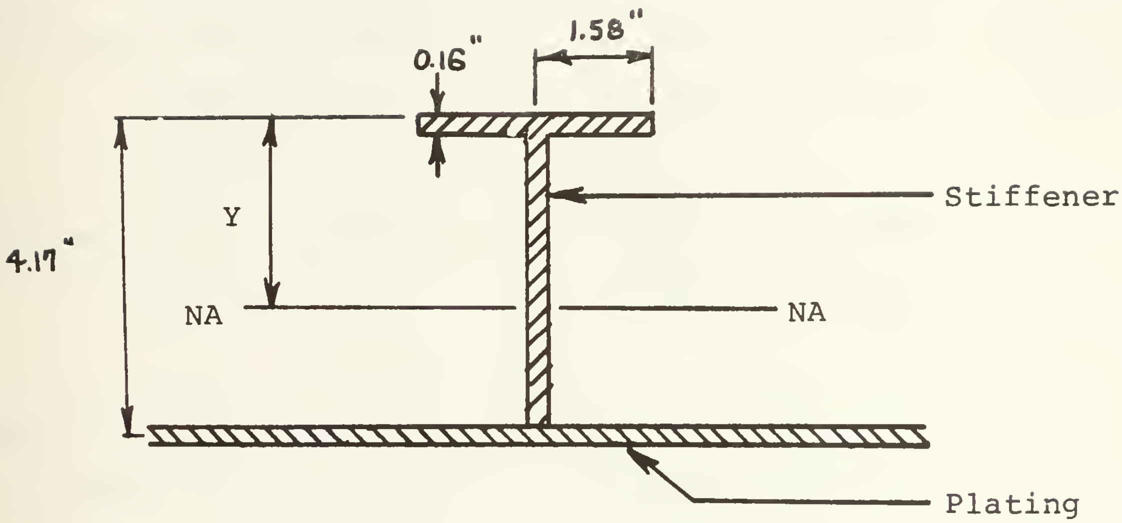
	HY-80	HTS	MS	AL(5456)
YIELD SAFETY FACTOR	1.22	1.12	1.18	1.24

The simplified comparison further indicates the greater conservatism as practiced in monohull design when compared with hydrofoils. However, a quantitative comparison is not possible due to the different formulations of the opposing stress criteria.

Section 4.3 - Comparison

Several approaches were employed in the comparison of the two design approaches. First, the allowable stress limits for the components of a typical structural element, as shown in Figure 14, were determined based on both hydrofoil and monohull criteria. In order to determine the stress limits from the monohull combined stress criteria, it was assumed that the load under consideration was at its maximum and the associated load was at its minimum. The results of this approach are presented in Table 8.

From this comparison two conclusions could be made. First, the hydrofoil criteria allows higher working stresses resulting in lower structural weight. Also, the differences in the load phasing approach of the two design criterias did not allow for an exact quantified comparison of design working stresses. This raised the question of which approach was correct. It would seem that the monohull approach more nearly accounts for the actual phasing of loads. Specifically, the hydrofoil structure would seem to be subjected to both impact pressures and longitudinal and/or side bending when broaching. In fact, in the preliminary design of the 2400 ton monohull, HYD-2, this procedure was followed.[9]



AL5456

$I_{yy} = 9.2 \text{ in}^4$

$Y = 3.14"$

$R = 1.74"$

$S = 9.84"$

$\ell = 39.37"$

FIGURE 14 - TYPICAL HYDROFOIL STRUCTURAL ELEMENT

TABLE 8

COMPARISON OF ALLOWABLE STRESSES

	Hydrofoil	Monohull	Comparison Ratio
Tension Critical			
Stiffener Primary Bending	21,000	10,000	2.00
Local Loading	14,000	17,000	0.82
Plating Primary Bending	26,000	10,000	2.60
Local Loading	26,000	21,000	1.24
Compression Critical			
Stiffener Primary Bending	22,000	16,800	1.31
Local Loading	22,000	17,000	1.29
Plating Primary Bending	24,000	10,000	2.40
Local Loading	21,000	16,800	1.25

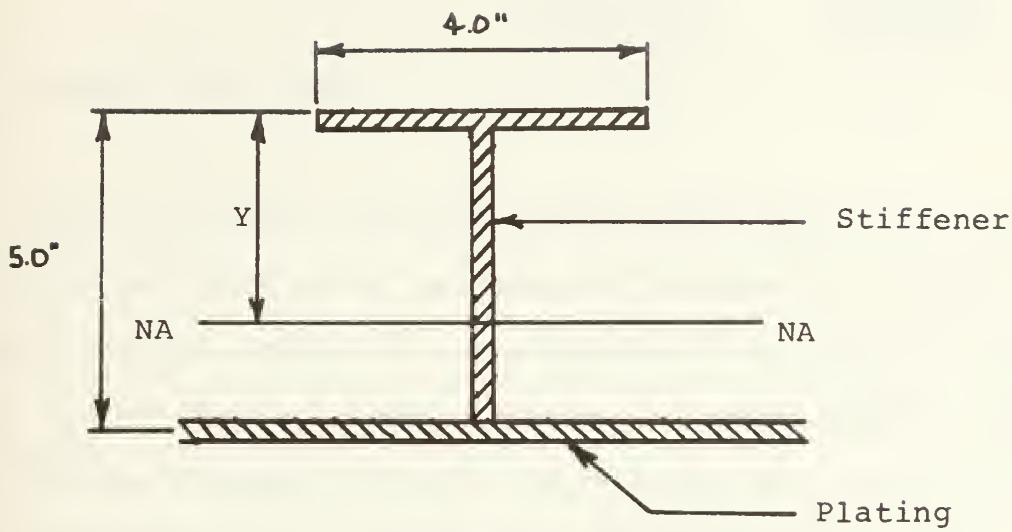
This is not to indicate that the monohull approach to load phasing is totally correct. The monohulls do not consider combat loads as acting in unison with other loads. It would seem that deck structure could be subjected to both primary bending and combat loads.

In the second analysis, the bottom structure of a comparable hydrofoil and monohull were compared. The characteristics of the ships selected are outlined below:

	PHM-1	PG-84
L	116 FT	154 FT
B	24.5 FT	24 FT
T	8.5 FT	5 FT
Δ	240 TONS	240 TONS

The structural elements compared are presented in Figures 14 and 15. Each structure was subjected to an analysis to determine its deviation from its prescribed design criteria.

The governing mode of failure for the hydrofoil structure was ultimate failure in the midspan of the element in the stiffener flange. Actually, the worst case was compression failure at the stiffener supports but this condition was reduced by local reinforcement. The monohull governing failure mode was ultimate failure, under compression, of the stiffener at the support. When these structures were



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$I_{yy} = 31.20 \text{ in}^4$

$Y = 4.4"$

$R = 1.79"$

$S = 12"$

$\ell = 48"$

FIGURE 15 - TYPICAL MONOHULL STRUCTURAL ELEMENT

compared by dividing the allowable stress criteria value by the values calculated, the following relative factors of safety or conservatism indices could be determined.

	HYDROFOIL STRUCTURE	MONOHULL STRUCTURE
Conservatism Index	1.07	1.67

This simplistic approach yields some rather startling results. No doubt there are some differences in technology between the two ships since the monohull was designed ten years before the hydrofoil. However, since monohull design approach has changed little in that time, this would not seem responsible for the drastic difference between the two ships.

The above approach underlines the apparent lack of concern on the part of the monohull designer for the reduction of structural weight. This is opposed to the hydrofoil designer's desperate need to reduce the structural weight to assure that the hydrofoils can become foilborne.

Section 4.4 - Summary and Conclusions

The major differences in hydrofoil and monohull design methodology and criteria are as follows:

--The hydrofoils employ lower safety factors and/or less conservatism than do the monohulls, qualitatively speaking. A quantitative comparison is not possible due to the differing stress criteria formulations. This would lead to higher allowable stress levels in hydrofoil structures.

--The hydrofoil approach does not consider stresses due to longitudinal bending and local loading as acting together as is done in monohull design. It would seem that the monohull approach is more realistic, since hydrofoils could experience longitudinal bending and impact pressure loading simultaneously during a broach or wave impact. However, this would result in high allowable steel levels in hydrofoil structures for similar size ships.

These factors combine to account, in part, for the superior structural efficiency of hydrofoils as compared to monohulls.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

It can be concluded that the structural weight efficiency of hydrofoils is primarily a result of natural differences. The utilization of aluminum in monohulls could reduce the structural weight an average of 39 percent which translates into 73 percent of the structural efficiency advantage enjoyed by hydrofoils over monohulls. This leaves only a 27 percent residual difference to be accounted for.

The remaining difference is the result of such factors as loads, safety factors, level of design detail, and construction techniques. Although the issue is not clear, due to a lack of actual load data, it is felt that the hydrofoils are designed to a higher load profile than monohulls. This is exactly the opposite of the expected trend as based on the superior structural efficiency displayed by hydrofoils over monohulls. Therefore, the differences in factors of safety, design detail, and construction techniques combine to negate the adverse load difference and account for the residual differences in structural efficiency of hydrofoils.

The various factors which combine to increase the structural efficiency of hydrofoils over monohulls can be ranked in descending order of importance:

--Material Difference

--Safety Factor

--Design Detail

--Construction Techniques

The above conclusions spawn some obvious, but nevertheless noteworthy, recommendations. First, in spite of the many obvious drawbacks inherent in the use of aluminum, it would seem imperative for the Navy to seriously investigate its utilization in conventional displacement monohulls. The forecasted weight savings alone would allow a typical destroyer to carry twice the payload weight. In the future, as crews are reduced due to essential manning, and weapon systems density decrease, due to containerization of missile systems and minaturization of electronics, the prospect of additional available payload weight will become increasingly attractive.

Secondly, it would be quite beneficial to reassess the complete design approach employed in monohull design. The load predictive techniques should be reconsidered to reflect the actual service load conditions experienced by the ship. Once the load profile can be adequately predicted, in spite of the construction materials utilized, the arbitrarily large safety factors could be reduced and the level of design detail increased to tailor the structure to the loads.

Although this would result in additional design cost of the ship, this is minimal when compared with either the ship's acquisition cost or the cost due to lost payload capacity.

Finally, the weight reduction techniques employed in hydrofoil construction should be considered to determine those techniques that would be appropriate for implementation in monohull construction. Although cost must be the governing criteria in deciding if these techniques are to be used in monohull construction, this decision cannot be properly considered by the monohull structural designer until both the actual increased fabrication costs and weight reduction impact for various materials are identified.

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APPENDIX A

WEIGHT GROUP BREAKDOWN

The following is the classification used in defining the weight categories used in the analysis described in Chapter 2. The weight group numbers are taken from the SWBS.[3]

SWBS WEIGHT GROUPS	BSCI WEIGHT GROUPS	DESCRIPTION
100		Hull structure
111	100	Shell plating
113	102	Inner bottom plating
114	101	Shell appendages
115	101	Stanchions
116	101	Longitudinal framing
117	101	Transverse framing
121	114	Longitudinal structural bulkheads
122	114	Transverse structural bulkheads
123	115	Trunks and enclosures
131	107	Main deck
132	106	Second deck
136	103	01 hull deck
141	103	First platform
142	103	Second platform
149	103	Flats

151	111	Deckhouse to first level
152	111	First deckhouse level
153	111	Second deckhouse level
161	119	Structural castings
162	205	Stacks and masts
163	120	Sea chests
164	117	Ballistic plating
165	127	Sonar domes
167	123 & 124	Hull structural closures
168	--	Deckhouse structural closures
169	122	Special purpose closures
171	125 & 128	Mast
181	--	Hull structure foundations
182	112	Propulsion plant foundations
183	113	Electric plant foundations
184	113	Command and surveilance foundations
185	113	Auxiliary system foundations
186	113	Outfit and furnishings foundations
187	113	Armament foundations
191	121	Ballast
197	150	Welding
198	151	Free flooding liquids
200	200	Propulsion plant

300	300	Electrical plant and distribution system
400	400	Command and surveillance
500	500	Auxiliary systems
567	--	Lift systems
600	600	Outfit and furnishings
635	607	Insulation
700	700	Armament
MARGIN	MARGIN	Margins
LOADS	LOADS	Loads

APPENDIX B

SHIP DATA

Weights, volumes and important design features of the ships analyzed in Chapter 2 are presented for reference in this appendix.

TABLE B-1 - HYDROFOIL CHARACTERISTICS AND STRUCTURAL INDICES

	UNITS	PGH-2	PGH-1	PCH-1	PHM-1	AGEH-1	HYD-7	HOC	HYD-2
∇	FT^3	10,813	11,824	30,015	35,873	94,530	179,871	221,800	382,585
V_{DH}	FT^3	2,407	1,424	4,235	7,480	12,790	52,295	65,836	113,565
V_H	FT^3	8,406	10,400	25,780	28,393	81,740	127,576	155,964	269,020
Δ	TONS	58.17	67.51	112.29	241.13	303.93	970.00	1378.00	2362.00
W_B	TONS	0.02	--	--	--	2.82	--	--	--
W_{FF}	TONS	—	—	—	5.00	--	--	--	--
W_{MR}	TONS	2.54	1.93	--	15.22	--	93.00	103.00	194.60
W_{LS}	TONS	42.03	54.17	85.74	185.33	232.69	711.00	885.00	1491.20
W_S	TONS	13.48	18.68	29.72	50.49	82.75	221.64	262.35	456.83
W_W	TONS	0.34	0.23	0.43	0.80	2.42	12.66[1]	25.57[1]	4.00
W_{DH}	TONS	0.97	1.58	2.21	4.64	5.22	21.52	36.67	62.77
W_{ME}	TONS	28.46	35.42	56.02	133.56	149.85	489.36	622.65	1034.37
W_{MEL}	TONS	21.24	27.23	43.53	94.94	101.98	398.90	405.25	770.85
W_{FD}	TONS	1.84	2.31	3.44	7.32	8.49	34.32	41.20	54.59
W_{FDL}	TONS	0.63	1.06	1.54	3.85	3.96	21.86	16.70	27.99
W_{MS}	TONS	0.80	0.98	1.22	2.29	1.79	13.15	14.08	25.56
W_H	TONS	9.80	13.72	22.27	34.33	66.58	123.25	163.94	302.57

TABLE B-1 (cont.)

	UNITS	PGH-2	PGH-1	PCH-1	PHM-1	AGEH-1	HYD-7	HOC	HYD-2
W_{HP}	TONS	4.82	7.27	12.13	19.00	27.79	72.80	78.51	173.14
W_{HS}	TONS	3.34	4.25	7.82	10.04	22.14	31.20	54.10	48.29
Δ/∇	lbs/FT^3	12.05	12.79	8.38	15.05	7.20	12.08	13.92	13.83
W_S/Δ	%	23.17	27.67	26.47	20.94	27.23	22.85	19.04	19.34
W_S/∇	lbs/FT^3	2.79	3.54	2.22	3.15	1.96	2.76	2.65	2.67
W_{DH}/W_S	%	7.20	8.46	7.44	9.19	6.31	9.71	13.98	13.74
W_{DH}/V_{DH}	lbs/FT^3	0.90	2.49	1.17	1.39	0.91	0.92	1.25	1.24
W_{FD}/W_S	%	13.65	12.37	11.57	14.50	10.26	15.48	15.70	11.95
W_{FD}/W_{ME}	%	6.47	6.51	6.14	5.48	5.67	7.01	6.62	5.28
W_{FDL}/W_S	%	4.67	5.67	5.18	7.63	4.79	9.86	6.37	6.13
W_{FDL}/W_{MEL}	%	2.97	3.89	3.49	3.51	3.89	5.48	4.12	3.63
Δ/V_H	lbs/FT^3	15.50	14.54	9.76	19.02	8.33	17.03	19.79	19.67
W_H/Δ	%	16.85	20.32	19.83	14.24	21.91	12.71	11.90	12.81
W_H/W_S	%	72.70	73.44	74.93	67.99	81.45	55.61	62.49	66.23
W_H/V_H	lbs/FT^3	2.61	2.96	1.94	2.71	1.82	2.16	2.35	2.52
W_{HP}/Δ	%	8.29	10.77	10.80	7.88	9.14	7.51	5.70	7.33
W_{HP}/W_S	%	35.76	38.92	40.81	37.63	33.58	32.85	29.93	37.90

TABLE B-1 (cont.)

	UNITS	PGH-2	PGH-1	PCH-1	PHM-1	AGEH-1	HYD-7	HOC	HYD-2
W_{HP}/W_H	%	49.18	52.99	54.47	55.35	41.74	59.07	47.89	57.22
W_{HP}/V_H	lbs/FT^3	1.28	1.57	1.05	1.50	0.76	1.28	1.13	1.44
W_{HS}/Δ	%	5.74	6.30	6.97	4.16	7.28	3.22	3.93	2.04
W_{HS}/W_S	%	24.78	22.75	26.35	19.89	26.76	14.08	20.62	10.57
W_{HS}/W_H	%	34.08	30.98	35.16	29.25	33.25	25.31	33.00	15.96
W_{HS}/V_H	lbs/FT^3	0.89	0.91	0.68	0.79	0.61	0.55	0.78	0.40
W_I	TONS	--	--	--	--	--	22.62	--	30.20

NOTES: [1]Contains structural weight margins that are over and above light ship margin.

TABLE B-2 - MONOHULL CHARACTERISTICS AND STRUCTURAL INDICES

	UNITS	PG-84	PGG	PCG	FF-1033	FF-1037	MONO-3	FF-1040	FFG-7	FF-1052	DDG-2	DD-963
∇	FT^3	48,596	70,100	125,100	242,397	296,700	460,610	396,900	514,922	481,000	453,700	1,194,122
V_{DH}	FT^3	9,914	22,600	35,000	30,948	41,200	94,000	66,200	152,000	119,500	111,700	240,860
V_H	FT^3	38,682	47,500	90,100	211,449	255,500	366,610	330,700	362,922	361,500	342,000	953,262
Δ	TONS	241.86	385.51	838.33	1769.50	2632.40	2891.57	3376.10	3605.42	3898.80	4525.50	7891.60
W_B	TONS	----	0.34	1.00	25.00	----	----	----	----	100.00	----	----
W_{FF}	TONS	----	----	----	----	----	----	97.70	16.68	----	----	15.50
W_{LS}	TONS	188.05	300.02	648.03	1229.00	1791.70	2061.40	2347.8	2749.07	2770.93	3277.40	5900.30
W_S	TONS	66.56	91.09	297.11	588.05	808.55	714.93	1057.94	1270.32	1294.02	1227.19	3111.29
W_W	TONS	1.87	1.35	4.36	17.56	19.69	9.79	28.17	18.69	31.45	30.23	83.26
W_{DH}	TONS	7.83	11.24	16.87	21.34	30.21	39.36	54.21	105.61	113.84	116.36	203.32
W_{ME}	TONS	121.49	288.93	352.90	640.95	983.15	1346.47	1289.86	1478.75	1476.91	2050.21	2789.51
W_{FD}	TONS	4.53	11.55	17.64	39.21	37.24	111.88	98.50	147.92	102.14	124.62	309.71
W_{MS}	TONS	4.49	4.32	10.29	21.34	22.04	48.05	46.39	61.53	53.91	62.87	123.18
W_H	TONS	49.41	61.29	223.69	499.23	717.14	444.25	848.47	939.49	986.97	916.20	2301.10
W_{HD}	TONS	30.70	32.23	113.43	222.12	289.15	----	455.34	540.02	580.93	549.68	792.56
W_{HS}	TONS	9.91	14.28	42.39	70.64	139.77	----	144.49	136.89	148.98	117.70	410.55
Δ/∇	lbs/FT^3	11.15	12.32	15.02	16.35	19.87	14.06	19.05	15.68	18.16	22.34	14.80
W_{MR}	TONS	----	26.38	42.46	25.50	17.80	268.88	92.60	86.79	----	25.00	89.90

TABLE B-2 (cont.)

	UNITS	PG-84	PGG	PCG	FF-1033	FF-1037	MONO-3	FF-1040	FFG-7	FF-1052	DDG-2	DD-963
W_S/Δ	%	27.52	23.63	35.20	33.23	30.72	24.70	31.34	35.20	33.20	27.00	39.43
W_S/∇	lbs/FT^3	3.07	2.91	5.32	5.43	6.10	3.48	5.97	5.53	6.03	6.06	5.84
W_{DH}/W_S	%	11.76	12.34	5.68	3.63	3.74	5.51	5.12	8.31	8.80	9.48	6.53
W_{DH}/V_{DH}	lbs/FT^3	1.77	1.11	1.08	1.54	1.64	0.94	1.83	1.56	2.13	2.33	1.89
W_{FD}/W_S	%	6.81	12.68	5.94	6.67	4.61	15.65	9.31	11.64	7.89	10.15	9.95
W_{FD}/W_{ME}	%	3.73	5.53	5.00	6.12	3.79	8.30	7.64	10.00	6.90	6.08	11.10
Δ/V_H	lbs/FT^3	14.01	18.18	20.84	18.75	21.95	18.32	22.87	21.90	24.16	29.64	18.54
W_H/Δ	%	20.40	15.90	26.68	28.21	27.24	15.40	25.13	26.06	25.31	20.25	29.16
W_H/W_S	%	74.23	67.28	75.79	84.89	88.69	62.14	80.20	73.96	76.27	74.66	73.96
W_H/V_H	lbs/FT^3	2.86	2.89	4.01	5.29	6.29	2.71	5.75	5.80	6.12	6.00	5.41
W_{HP}/Δ	%	12.69	8.38	13.53	12.55	10.98	----	13.49	14.98	14.90	12.15	10.04
W_{HP}/W_S	%	46.12	35.38	38.18	37.77	35.76	----	43.04	42.51	44.89	44.79	25.47
W_{HP}/W_H	%	62.13	52.59	50.71	44.49	40.32	----	53.67	57.48	58.86	60.00	34.44
W_{HP}/V_H	lbs/FT^3	1.78	1.52	2.03	2.35	2.54	----	3.08	3.33	3.60	3.60	1.86
W_{HS}/Δ	%	4.10	3.71	5.06	3.99	5.31	----	4.28	3.80	3.82	2.60	5.20
W_{HS}/W_S	%	14.89	15.68	14.27	12.01	8.74	----	13.66	10.78	11.51	9.59	13.20
W_{HS}/W_H	%	20.06	23.30	18.95	14.15	19.49	----	17.03	14.57	15.09	12.85	17.84

TABLE B-2 (cont.)

	UNITS	PG-84	PGG	PCG	FF-1033	FF-1037	MONO-3	FF-1040	FFG-7	FF-1052	DDG-2	DD-963
W_{HS}/V_H	lbs/FT^3	0.57	0.67	0.76	0.75	1.23	----	0.98	0.85	0.92	0.77	0.96
W_I	TONS	----	----	----	----	----	40.35	----	----	----	----	----
W_A	TONS	----	----	----	----	----	48.98	----	----	----	----	----

APPENDIX C

ALLOWABLE STRUCTURAL PROPERTIES

Selected tables and design curves for the allowable properties of various materials are included in this appendix.

TABLE C-1

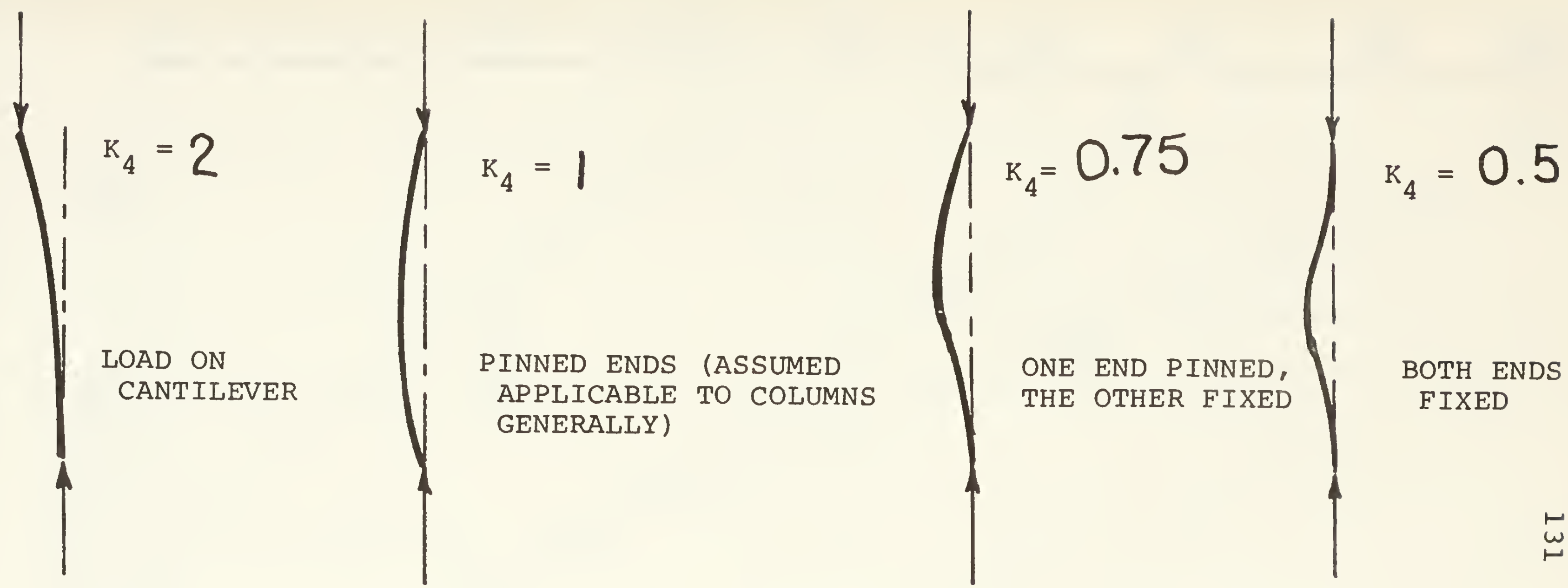
ALLOWABLE PROPERTIES OF WELDED ALUMINUM ALLOY 5456

Structural Element	σ_{UM} (PSI)	σ_{YM} (PSI)	σ_{YMC} (PSI)
Extrusions - H111	41,000	24,000	22,000
Plates - H117			
0.125 to 1.50"	42,000	26,000	24,000
1.50" to 3.00"	41,000	24,000	23,000

TABLE C-2

MONOHULL ALLOWABLE STRESS LIMITS FOR WELDED MATERIAL

Material	σ_{YM} (PSI)	σ_{ALL} (PSI)
MS	33,000	27,000
HTS	45,000	38,000
HY80	80,000	55,000
AL5086-H111	16,000	14,000
AL5086-H117	22,000	18,000
AL5456-H111	21,000	17,000
AL5456-H117	26,000	21,000



NOTE: Values less than unity should not be used unless all bending stresses, including any secondary bending, are taken into account.

FIGURE C-1 - END-CONDITION COEFFICIENTS FOR SLENDERNESS RATIOS OF COLUMNS

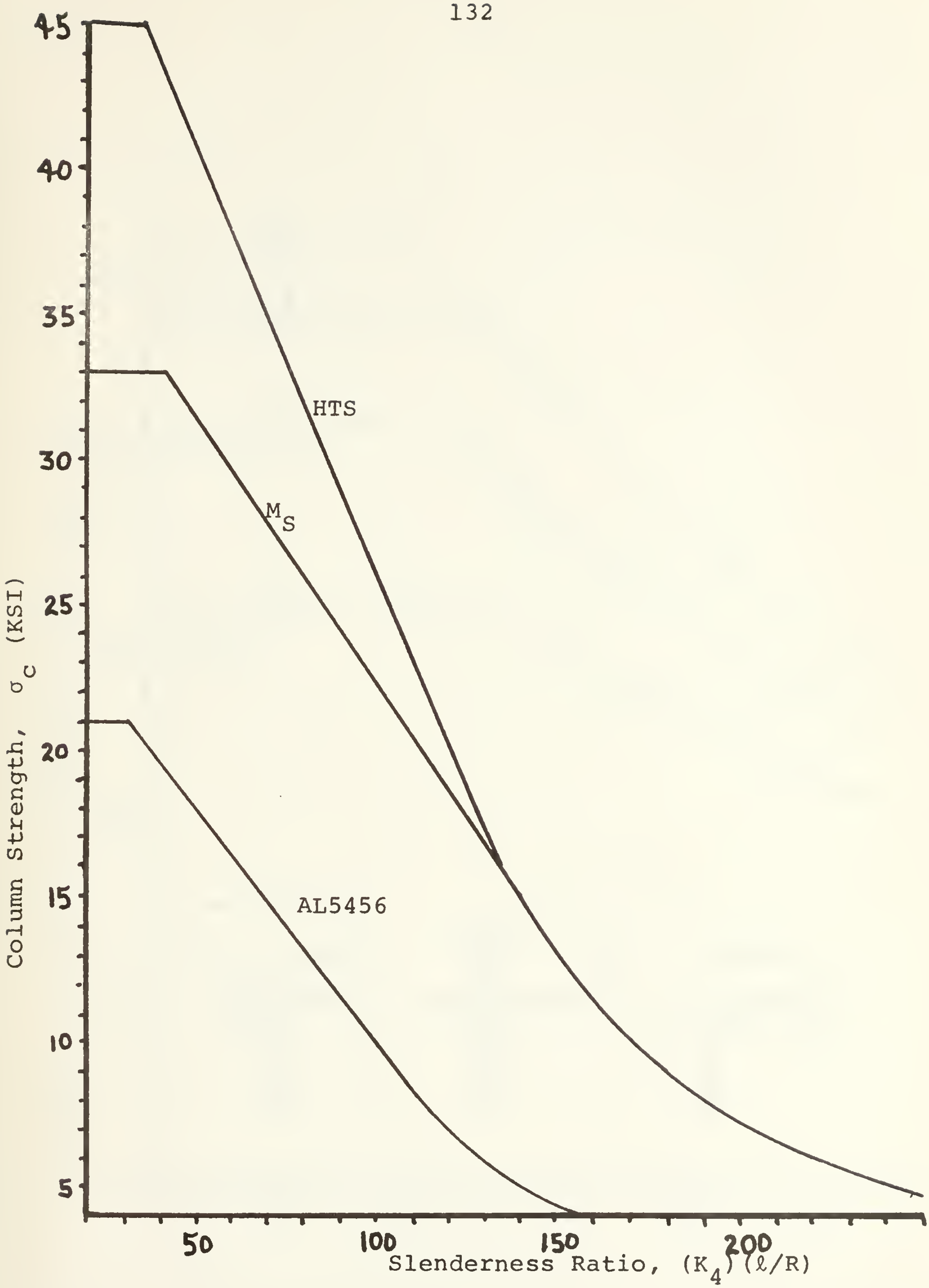


FIGURE C-2 - ALLOWABLE STRENGTH OF COLUMNS

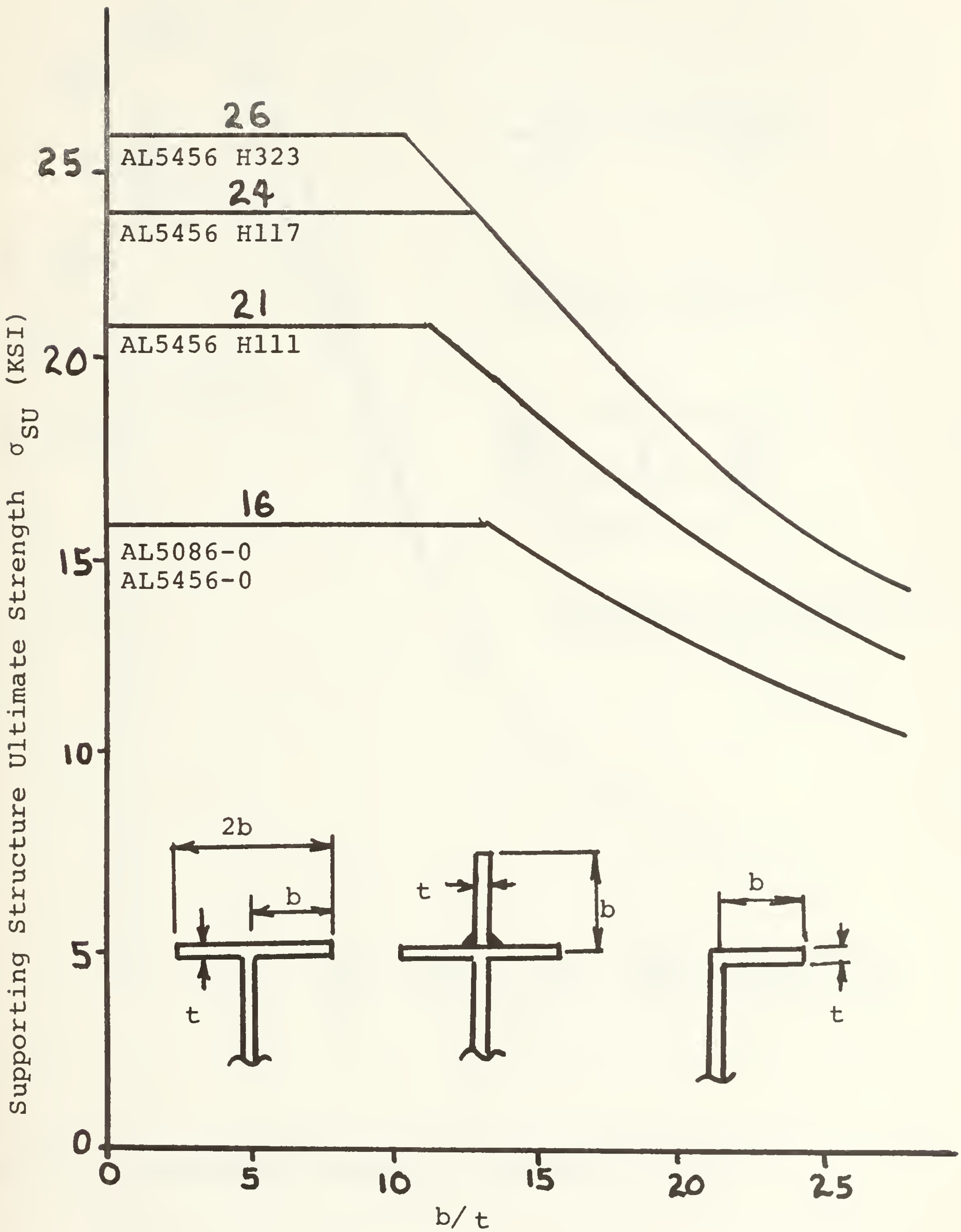


FIGURE C-3 - ALLOWABLE ULTIMATE STRENGTH OF SUPPORTING STRUCTURES

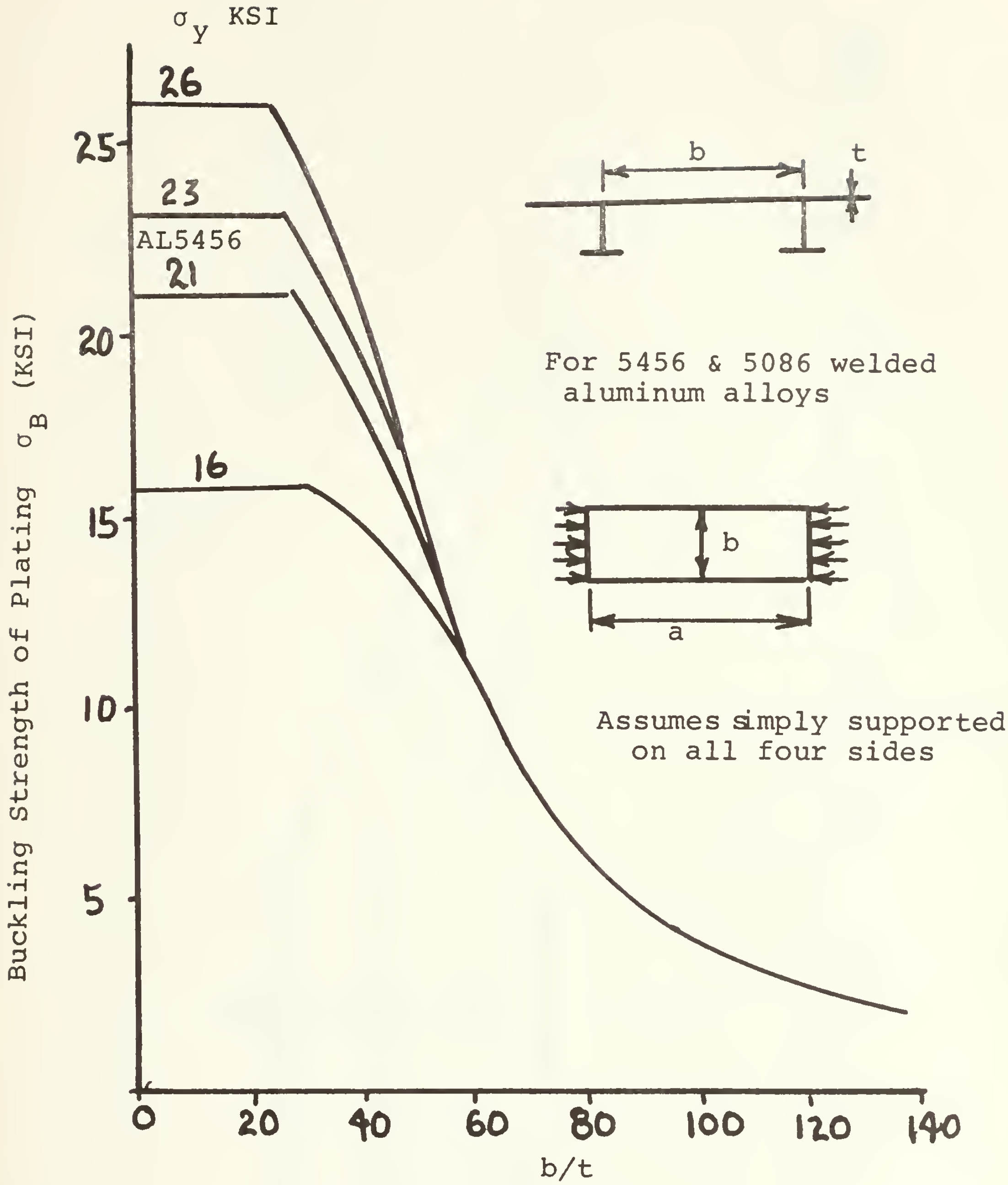


FIGURE C-4 - ALLOWABLE BUCKLING STRENGTH OF PLATING

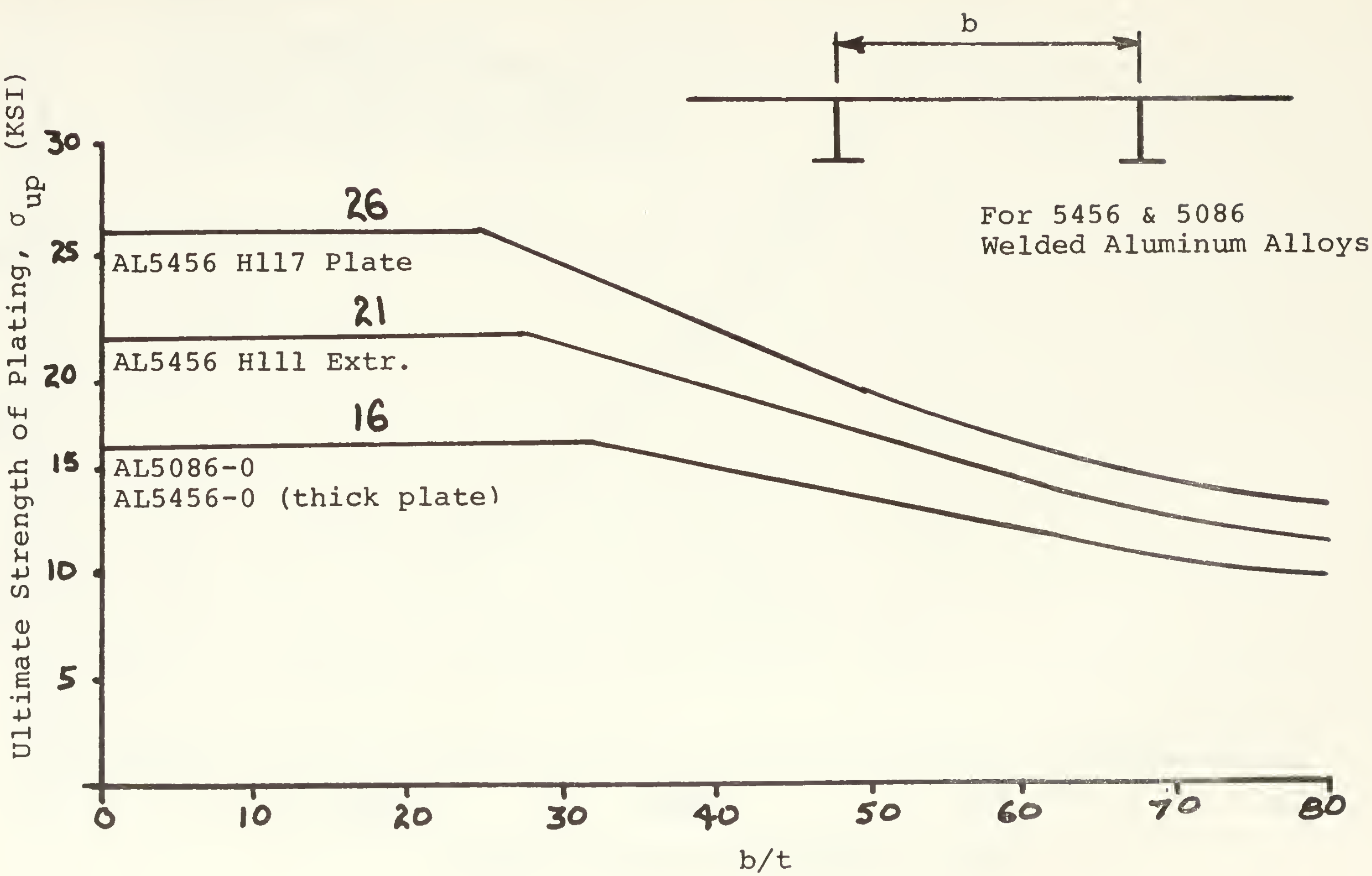


FIGURE C-5 - ALLOWABLE ULTIMATE STRENGTH OF PLATING

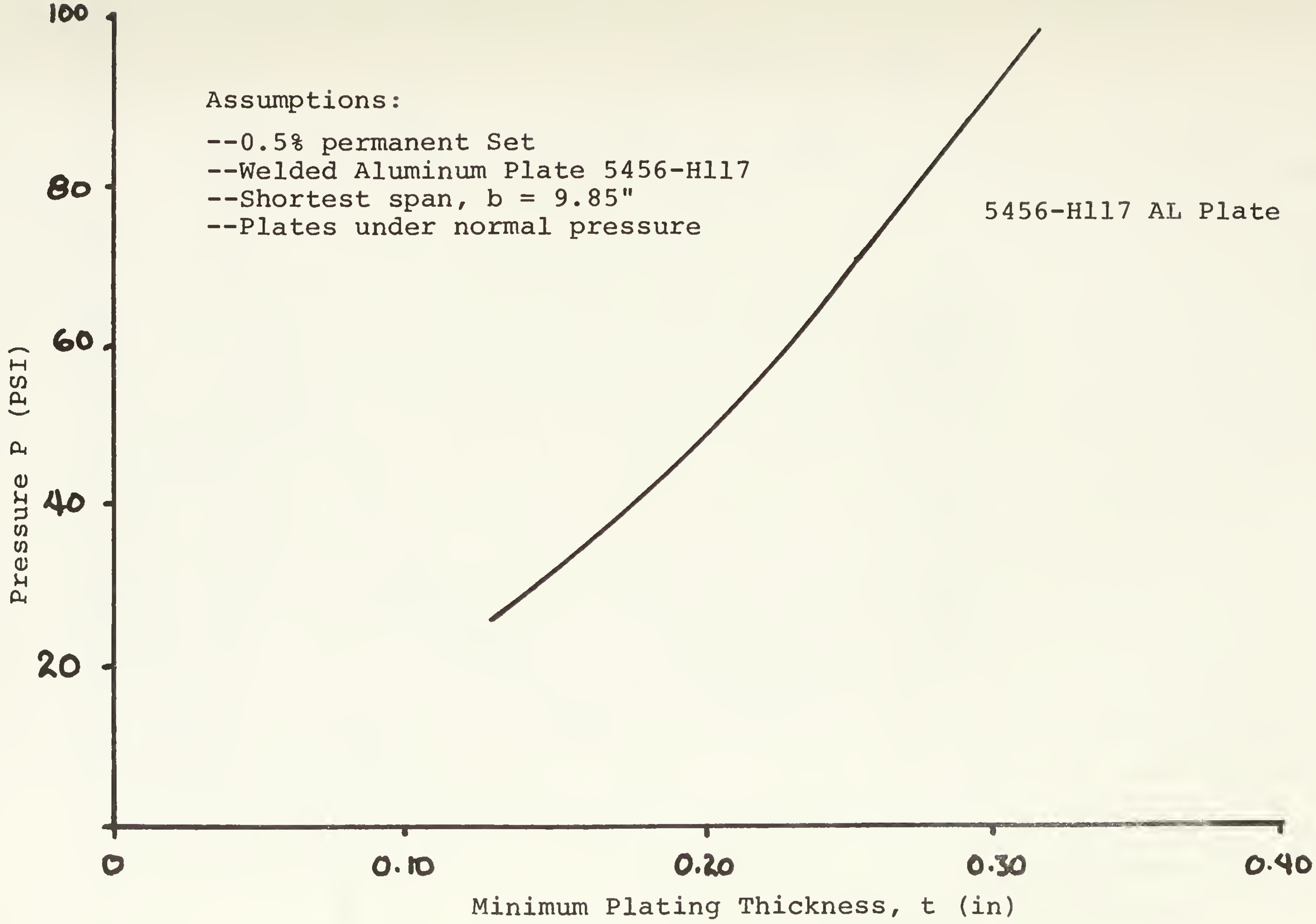


FIGURE C-6 - PHM MINIMUM PLATING THICKNESS UNDER NORMAL PRESSURE LOADS

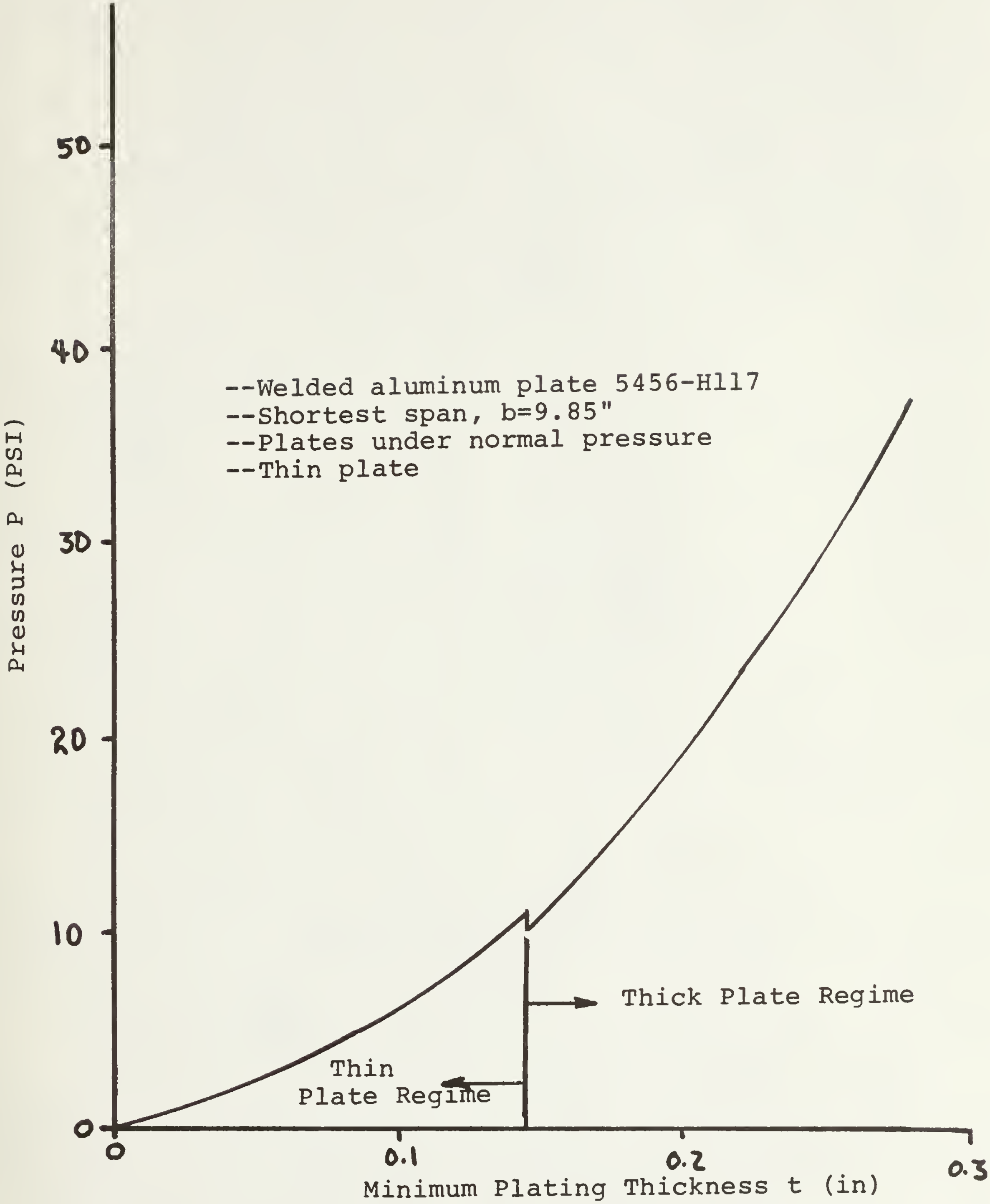


FIGURE C-7 - PHM MINIMUM PLATING THICKNESS FOR HIGH LOADED STRUCTURE

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